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A SYSTEMS APPROACH FOR CREW STATION DESIGN AND EVALUATION

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This report documents the development and current status of the Crew Systems Development Branch's (AFWAL/FIGR) methodology for designing and evaluating crew stations for new Air Force aircraft. The report begins with a historical background for the problem area, and then overviews the methodology as employed today. This is followed by a detailed discussion of each of the major stages of the process. The report concludes with a discussion of resources typically involved in cockpit design efforts and a section on crew system testing and evaluation. Also included is a 300 item Bibliography, sampling the more than

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10,000 relevant articles, reports and test documentation found in AFWAL/FIGR's Control Display Information Center (CDIC).

FOREWORD

This report discusses the background and current practices employed in the development and evaluation of crew systems for aerospace vehicles. It draws upon experiences in a research and development group of the Air Force for background and details the steps in the process as they are currently perceived.

It is a report on progress made in applying and expanding upon the philosophy presented in ASD TR 61-545 (Ref: 1). That report, "Cockpit Control-Display Subsystem Engineering", was based upon eight years of experience and proposed a method and a management philosophy for developing cockpits as integral parts of weapon systems. This is, in effect, a final report by the authors on twenty years of work for that proposal.

A prime goal underlying that philosophy was the establishment of effective Air Force dominance and control over the cockpit and in turn over the system and system effectiveness. Recent experiences are highly encouraging.

The development of a methodology for crew systems has been a long and arduous affair. Significant steps have advanced the capability during the years but the total advance has not been adequately documented. In general, the documentation has tended to address specific techniques or facets. It is the intent of this document to consider the cumulative experiences and practices of the Crew Systems Development Branch (FIGR) and its predecessors and to present a summary of a practical methodology for crew system development and evaluation in its present state of development.

In reviewing reference material, an interesting observation is that reports on methodology are not very perishable. Bibliographic material of twenty years ago is still germaine. A note in a 1961 report (Ref. 1) said that the nature of the work changes with the passage of time - still true - but the methodological extractions remain valid. With the passage of time we have been able to expand the detail treatment.

The methodology and (management) philosophy employed in crew system development was first described by Kearns and Ritchie in 1961 (Ref. 1). That approach has remained as the theme and has been expanded upon by the developments that have ensued and by the many engineers and scientists who have worked in or for the branch. Expansion upon this theme has led to a comprehensive approach to Control Systems and the advocacy of a Control System Science. Expansion beyond the scope of control systems, while a viable option, has not yet reached a satisfactory state of understanding and documentation.

In reviewing the 1961 report (Ref. 1), I have found that the changes since then relate to generalizations on technical groupings (technological advances have given us flexibility and more opportunities), and level of discussion (the experience of twenty years provided a wealth of detail for filling gaps and expanding upon concepts). By and large, the philosophical thrust has remained constant.

Control-Display as a uniquely identifiable work area within the USAF received its prime impetus in the early 50's. It has progressed steadily in the development and validation of techniques for advancing the systems considerations as a means to providing suitable capability for the crews of USAF aerospace vehicles. To provide for continuity and to clearly establish the basis for current methods some review of the pertinent history is provided. Section I addresses this background.

The specific process is discussed, as an overview in Section II and in detail in Section III.

The methodology, as now perceived, includes many of the ramifications not ordinarily described in a technical development. Not only people skills, but organizational interactions can profoundly affect the course of a technical effort (Ref. 2). In a system of significant complexity the effects of these external factors are of such magnitude that they must be considered in the conduct of the technical effort. This concern is addressed in Section IV.

While it is not the intent of this document to delineate tests, there are some aspects which are believed sufficiently significant and out of the ordinary, to warrant discussion. This discussion is contained in Section V.

This documentation was prepared by ORLOC under USAF Contract F33615-81C-3619. Mr. Richard Moss (AFWAL/FIGR) was the Project Engineer. The report was authorized under Project/Task 2403.

Special acknowledgement is made of participation by Dr. Malcolm L. Ritchie and the support of Greg J. Barbato.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES


CREW SYSTEMS DEVELOPMENT

SECTION I

INTRODUCTION

In the original concept for this methodology (Ref. 1) the following divisions were used:

Preliminary Investigation
Preliminary Design
Research
Development
Test and Evaluation

These are probably as good as any. A difficulty in discussing the program is that it is a complete entity, and any attempt to partition the program produces arbitrary and artificial pieces. Yet, some such process as partitioning is necessary for purposes of discussing details of the work. I hope that the readers and discussants will retain the thought that the pieces must be viewed in the context of ONE program. The proverbial story of the blind men examining an elephant comes to mind when attempting to discuss a weapon system - we can talk of legs, tail, trunk, torso as did the blind men but those items exist only as part of the whole and have no meaningful existence as independent parts.

Our interest, initially, was centered on the development of the cockpit. Our goal, as stated earlier, was to be able to present requirements with sufficient specifity, clarity and scope as to assure the Air Force that the final design would be suitable for the job and satisfactory to the crews. Not clearly stated but implicit in our effort was the intent to be able to measure proposed designs so as to determine the degree of compliance with specifications. The first major effort (Ref. 4) (Ref. 5) underscored two important points. (1) Even a small effort at improving the design in a system context could produce impressive results. (2) The cockpit relationship to all other parts of the weapon system was such that any change in the cockpit was reflected elsewhere and any change in the weapons system impacted upon the cockpit.

This second point may seem obvious but at that time period even adjacent instruments were treated as independent entities.

THE START

A common concern in the early 1950's, was the congestion on the instrument panel and the lack of space for adding new devices. New systems clamored for space. One of these, Data Link, could provide command information to the pilot for effecting intercept missions. There was no ready answer on how to add it to the panel.

The "Whole Panel Program" (Ref. 5, 6, 7) was initiated to address this issue. It was intentionally limited to a scope which was believed to be within our capability to address effectively. As Mr. Knemeyer put it, "Don't bite off more than we can chew." The intention was to produce improvements which could be immediately realized while simultaneously providing insight into how to deal with the broader aspects yet to come. This first step produced substantial benefits for the Air Force. One product, the "T" scan, became the new standard for Air Force instrument panels, replacing the "Sacred Six" and the "Basic Eight" arrangements.

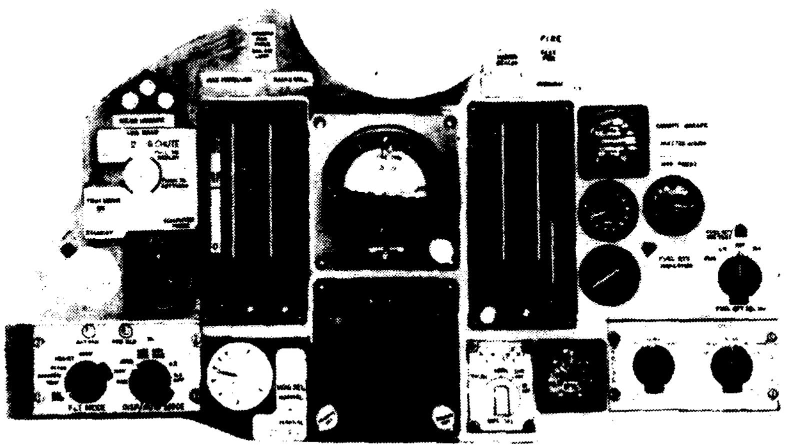


Figure 1. The Whole Panel

The Flight Director became de rigueur for all subsequent panel proposals. Vertical scale displays became very modish. None of this came easily, it was a long, difficult and expensive effort. The resultant design appeared in the F-102, F-106, and the F-105 as the Air Force Advanced Instrument System. Variations have been used in all subsequent Air Force aircraft.

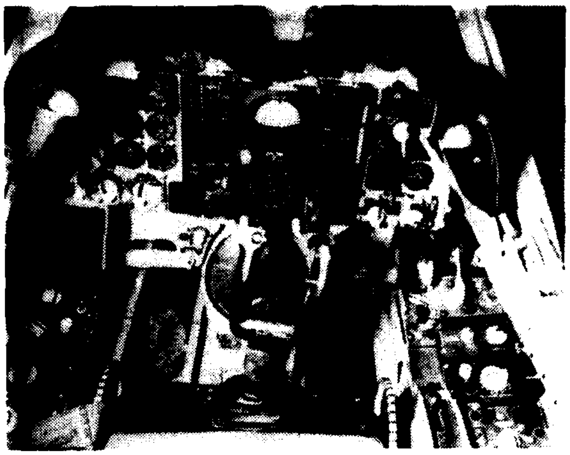


Figure 2. The F-102 Cockpit

IMPLICATIONS DISCOVERED

Several key issues were identified. They included: display development; interpersonal relations; technical development; and systems integration.

Display Development: A systematic approach to satisfy the pilot's needs for display was the key theme. (The pilot oriented approach has continued to be a dominant theme for the display problem from the viewpoint of the pilot. Several things were evident. There were, seemingly, conflicting signals being given from various instruments. Interpretation of an overall picture required considerable mental manipulation of the various scales and dimensions used. There was a need to harmonize displays from one instrument to another and to make them as useful as possible. In our concern to improve the cockpit in terms of the pilot viewpoint, we solicited the expertise of disciplines skilled in determining the optimal configuration for use by humans. Engineering psychologists were asked to participate in the design process. This request set precedent that has produced an abundance of benefits. The inclusion of this specialty area into the design process from the initiation of a project has been a key factor in our successes.

Interpersonal Relations: Interpersonal relations among members of the development community turned out to be a significant issue. Each component was the sole domain of a champion (an expert, a czar). The attempt at harmonization between instruments required that each czar relinquish some of his authority, some of his domain. There were conscientious concerns expressed by these people. They had no background data to support the contentions. It appeared to conflict with items which were then of great concern (GFE, standardization, mass production, etc.) The probability of success for such a significant change appeared to them

to be slim. Their technical world pivoted around their specialty and the idea that a "system" engineer could give their area (as well as many others) adequate understanding and consideration was foreign to their thinking. They required proof that the result would be beneficial. (With the need for such proof, improvement came slowly.)

The engineers reacted to an inferred criticism when experimental psychologists were employed to test displays and controls. Human engineer became the label for these people and developed into a popular buzz word.

Actual design involves compromises. The field of "Experimental Psychology" was deeply involved in research on principles and the idea of some scientists participating in compromises was distasteful to the purists of the field. So the psychologists also experienced stress.

Technical Development: In the technical area there seemed to be challenges on several frontiers. Servomechanisms were not new but they received considerable impetus in this program. Requirements conflicted with restrictions in that much had to be done in a small space. Density (space occupied by components) in the vertical instruments reached 90%. For the first time, very expensive instrument models were used to develop acceptable lighting. This was a consequence of the sophisticated displays, the large faces and the concern for a balance across all of the instruments. The innovative technique of wedge lighting went into production from this program.

System Integration: System integration was employed in the linking and switching of signals from black boxes to displays and revealed many benefits to be derived from this idea. It too became a buzz word. Interfacing black boxes was a systems engineering task. But organizations were concerned about jurisdiction.

The interaction of the cockpit with all parts of the system has significant implications on Weapon System design. In fact, it is a unique relationship. No other component or subsystem has such a relationship. It affects or is affected by every other facet of the Weapon System by virtue of the need to exercise jurisdiction over the entire weapon system. The cockpit is an intimate part of the weapon system - not an adjunct to provide a place for the pilot.

We ultimately developed the label "Crew System," meaning this intimacy of cause and effect between the cockpit/crew and all other elements of the weapon system. This "crew system" is, in some respects, a phantom system. It is not independently designed and built. It is really a way of looking at some aspects and functions of each of the other parts as they relate to the functioning of the crew in accomplishing the mission. It is a dependent system. The functioning of the crew is affected by design changes in a subsystem. If each subsystem pursues its own course, then the crew functioning is subject to unpredictable changes. Not a very healthy condition from the standpoint of concern for mission effectiveness.

The crew system came to be viewed by us as comprised of the crew, the crew compartments, the instruments, the controls, the phantom structure just mentioned, and the gestalt functioning of the weapon system. The problem was to bring about an efficient design for mission accomplishment. As we saw it, improvements in individual displays were necessary and could be pursued immediately. Improvements in crew systems were a far different matter. In the crew system issue it is necessary to consider relationships with the whole gamut of developers involved in a weapon system program.

A very difficult challenge was the coordination needed across all design efforts, in order to realize the benefits of systems integration. In the design and development of a weapon system, literally thousands of engineers and scientists are engaged. Each of them are addressing fairly specific problems with defined boundaries. These specifics are the "legs," "trunk," "tail," etc. of the system. The very magnitude of numbers (and independence of spirit) militate against adequate control. (I don't mean to imply resistance by the people. These are people with integrity and competence. They do the best job they can - as they see it.)

It was considered, therefore, that a logical method to gain the effects of control is to be found in the structuring of the problems. If a scientist is presented with a problem, properly structured in the system context and adequately defined, then the solution will fit the system and can become the system.

SCOPING (Where to go)

A singular reaction to the Whole Panel effort was the oft repeated questions "Why didn't you go further? Why stop at just the flight instruments?" We, of course, had restricted ourselves to what we considered to be within our capability. We were thoroughly steeped in flight control and flight instruments - so much so that we did not need to formally document the problem which our "system" was addressing.

If we were to expand then we would have to define a new scope and develop an acceptable logic for the newly defined boundaries. We had become very conscious of the need to explicitly identify and consider every conceivable detail of the problem and the system. Expanding beyond the areas of our immediate expertise required considerable care.

A really difficult thing was to expand our concerns across the system and yet not encroach or threaten the other system designers.

Over the years we have expended substantial effort in understanding a problem only to find that we had restricted our scope of interest too much. In successive programs we expanded the scope of our initial problem definition (from flight instruments to Whole Panel to crew system to mission) and put increasing emphasis upon understanding (or relating) that even the smallest element is influenced by the broad system

objectives and constraints. The challenge was - where to draw the line - how to establish the necessary information without steering each engineer into broad mission analysis for which he was neither equipped nor interested.

(By no means did we start out to address the whole scope of this ambitious idea. We puttered along, unaware of the magnitude of the undertaking, a fortunate happening. If we had known the true extent we might have been reluctant to start.)

It became clear that mission objectives, mission effectiveness are the goals and the constraints. We have found that as we understood the application better, we did a better job. . . No . . . let me rephrase that. As our understanding of the application improved then our ability to convey criteria (needed characteristics of performance) to vendors and to subcontractors became more satisfactory (to them and to us) and the resultant system became better.

> If we could understand the crew/system interface well enough and could relate it to mission, then perhaps we could influence the problem description such that the factors affecting the crew systems would be adequately expressed as criteria.

We haven't satisfied ourselves as to the complete answer as yet but we feel elated that we have made much progress.

DEFINE THE PROBLEM

We originally defined the starting point for our methodology as the point when a general mission concept is defined. The label used was PRELIMINARY INVESTIGATION with the objective being, to understand what is required. What we did was to start talking to pilots about our ideas and their perception of their job and needs.

There has always been a transfer of information between a pilot and a designer. What we were after was to achieve an improved understanding.

We had found that all too often our limited appreciation of operational details resulted in not even knowing what question to ask of the crew. As we improved we then found that the crew could not always answer the question without much introspection. Often they had to consider the question while going through a mission before coming up with the answers.

> It is not enough to say "We want one degree sensitivity in pitch." The designer must understand why the pilot told him that - in what context, for what purpose, under what conditions, and a thousand other questions.

Semantics and convention were fearful enemies of communication. Initially many people did not see any significant difference between the two following statements: "I need an attitude indicator," and "I need to know the attitude of my aircraft." We reached the point where in this example the statement changed to -

> "I need to control the flight path of my aircraft, therefore I need to know and control the flight path vector. Pitch, roll, yaw and throttle are the only means of control which I know are available. I can operate with displays which show altitude, rate of climb, speed, heading, pitch, roll and yaw. Possibly I can do better with a direct display of flight path vector." (A pitch trim is a crude substitute for flight path angle which is sometimes useful over a limited range.)

A natural development out of this experience was to have our lead people join with the crew in an effort to educate one another and to mutually define, in great detail, the performance required in order to complete a mission and to identify all of the ramifications that influence or constrain that performance.

It was very satisfying when new crews, in talking to our designers, concluded that we were experienced crew members. That was a milestone indicator of the effectiveness of the communication effort.

As this aspect evolved, some ordering of the process took place - for transfer to other teams and other programs - for organizing data according to subsystem needs - for assurance of continuity. This included documenting several iterations expanding upon the Statement of Need (SON). The resultant description was organized according to the needs of the engineering community, contained considerably more detail than the original SON and was consistent with the desires of the customer. As a companion to the "Need" statement, a description of how the vehicle would be used was developed. This was a narrative, from the crew perspective, describing the manner in which the crew expected to use the weapon system in the performance of the various missions.

The Preliminary Investigation (Problem Definition) has reached a level of maturation that is very satisfying. That is not to say that it is complete, only that there is no question as to its workability and value.

SOLVE

Conventionally, when the design starts, many teams press forward in the area of their expertise. They have received their marching orders and set out to build their thing (wheel, brake, engine, airframe, fuel cell) and they are prepared to build the best they can as judged by their peers in their technology. If they can meet the stated requirement (fit the space, meet the weight, come in within cost), then they've done a good job. Unfortunately, that does not insure a good system, at least it hasn't worked out that way.

If the resultant weapon system falls short of hoped for capability, it is hard to identify one of the subsystem designs as THE primary cause. The subsystem designers did what was asked and they can prove it. They have batteries of tests which are used in the design process of each specialty area. As the designer proceeds, he has a means of measuring progress and of measuring compliance. If the design starts to deviate from desired conditions, it can be readily detected and put back on course before it develops into a catastrophe.

It appeared to us that two points were of concern: (One) There had not been any adequate means of testing the functioning of the crew system during the design process (comparable to the test batteries used by the subsystem designers) and (Two) there were no meaningful criteria to be used in a system evaluation if the means were available.

Our efforts in terms of the testing involved the use of simulators. This allowed us to represent an entire cockpit while measuring performance on a specific display or control. The use of pilots as subjects improved upon the value of the subjective opinions. For any given device it was possible to load the pilot down with a flying task which exercised that particular device. Concentration was upon improved experimental techniques and that absorbed a considerable amount of time and resources. In the earlier years, at least, we felt that we had made great progress.

The second issue did not seem to respond as well or as rapidly. It would be highly desirable for the crew system group to be able to specify subsystem and component functioning in terms of their crew system function and to be able to assess the impact of the myriad of component variations upon system performance. The small daily changes among many efforts can accumulate to significant variation in system performance - a sort of gestalt of perturbations.

What appeared to be needed was a more thorough determination of the requirements for each item with emphasis upon delineation of the crew system aspects. Also needed was a means for continuing assessment of the collective aspects of these items in their system context and mission applicability.

Delineation of the requirements turned out to be a two pronged effort. One was concerned with supplying a greater level of details to be used by the individual designers. The other was a need for comprehensive requirements descriptive of the total collection taken as a system. (The Design Concept)

Assessment of the collective aspects of the pieces while functioning as a system was a real puzzlement. If we were to measure how the collective pieces functioned when employed as a system, then we had to describe that system functioning. The desired functioning was one or more missions.

Design Nattative.--In our efforts to understand the problem, we had drafted narratives of how the crew expected to use the vehicle. When

we iterated this to describe how the vehicle must function in order to be responsive to the crew expectations we had the start of system oriented criteria for crew systems. Our "criteria" for system performance was a detailed description of the system behavior in performance of the mission. This description was called our Design Scenario and it became the bench mark for assessing capabilities of system designs.

Design Concept.--The key players in this crew system activity (which we began to call "core group") devised overall system concepts (including features beyond their ken). These concepts were based upon their appreciation for the effective use of the human in combination with the technical capabilities afforded by the laboratory efforts. It required a broad based awareness of advances in physical technology and a good appreciation of human behavior and physiological factors. The system concept produced was a straw man device. It provided a basis for discussions with the many specialist organizations and for a continuing dialogue with requirements people and crews from the ultimate using command (the customer). As discussions progressed, the concept was modified to respond to the expertise of the consultants but always retained the crew system concerns. Tact and skill in human relations is an important ingredient for the core group members.

With this approach a general (or functional) description of a viable system emerged. It did not define hardware but included descriptions of the capabilities, functions and performance that many experts had testified as practical (based upon existing hardware, state-of-the-art for their field, or extrapolation of current R&D). The conceived system was at a practical forefront of technology.

(This is comparable to the concept of architecture for a computer design - in this instance the architectural design for the total system.)

It was in this stage that a partitioning evolved. Although not constrained to traditional divisions, it frequently reaffirmed them (e.g., communications, navigation) but modified them according to system oriented considerations. Consequently, specialized teams could be formed and address their problems, not as independent entities within the system, but as essential features of one system where the interplay among the subsystems is as significant in influencing their design as is the state of their particular technology.

Any design process, as it progresses, involves compromises. This usually means that you can't realize a design objective as you had expected because of a factor which you had not previously known. Therefore, the design becomes different in some respect. The designer looks at alternatives and selects based upon his judgment. This judgment relies heavily upon his background experience (normally his field of specialization). It was our thought that the designer have sufficient information about the system (and an efficient communication with the core team) such that the selection of alternatives include more awareness of the system implications.

(It is details or lack of details that can kill you and we wanted to improve upon the designer's consciousness of the details that were system related and mission related and therefore would react to his compromises.)

For the cockpit it is conceivable that every instrument, every device is provided by a separate contractor. Therefore, the effect of compromises in each design could have (and has had) a devastating effect upon system capability. Control or approval of each such change by a central authority would cause a tremendous burden and delay to the program. Awareness of the systems implications by the individual designers appears to be the only efficient and effective method for achieving reasonable (tolerable) compromises.

Design Scenario.--A mockup of a proposed cockpit design is not uncommon. Our variation was to use it (1) earlier than is conventionally done, as a means to assist in defining details of needed function and performance, and (2) for assessing the aggregate of these specified criteria in a systems context in the performance of the missions.

As ideas for new displays developed, particularly those that were appreciatively different or involved, they were mounted in cockpit mockups. It was a lot easier to explain their functioning when they were viewed in the context of the crew station. In explaining the more complex ideas, it was necessary to discuss the role and problem at issue. The "Design Narrative" provided the base. This seemed naturally to lead to role playing demonstrations in the mockup which were showing the explanation in terms of the "Design Narrative." For limited problems (part task/part mission) these informal discussions sufficed. With expansion in scope and in the numbers of subjects, some formality was required to provide consistency. Documentation was prepared to describe the role playing event, basically who did what and when. It evolved into a time based description of the roles of the crew members in accomplishing a mission. Exposing several crews to the same scenario provided an opportunity to obtain reinforcement of some crew reactions, a useful output. The psychologists attached to our teams really capitalized upon the opportunity to acquire subjective data which assessed the utility of a set of displays. Of particular merit was the fact that the subjects were viewing the displays in the context of their intended use. Over the years this progressed to the point of developing a narrative covering the entire menu of missions to be performed. Subsequently, we put all of the missions of a planned vehicle in one flight plan. Although unrealistic in terms of operations (no one flight could be expected to perform every one of the missions for which the system had capability), it was a way of compressing all the design challenges into one bundle and providing a consistent means of addressing these problems. This became known as our "DESIGN SCENARIO."

Dynamic Review.--We assembled all of the proposed device designs into a cockpit mockup and flew the mission as defined by the Design Scenario. . . (a paper mockup, imaginary flight, real crews). As glitches were discovered, we could redraw/relocate/redesign and refly. We then were in a position to specify details which would otherwise be uncontrolled. As teams developed changes we could readily assess the impact upon crew and mission.

We then were in a position to specify details which would otherwise be uncontrolled. As changes were proposed we could readily consider the impact upon crew and mission.

Although made only of paper, several different kinds of problems can be effectively addressed in this mockup. (1) Our description of the mission (the real crews will catch glitches); (2) Crew size and crew role (several different design concepts can be tried and an informed judgment made as to their probability of success.) This is a way for capitalizing upon the thousands of experiences of the operational crews. These experiences will be implicit in the comments and judgments of the subject crews. (Thousands of experiences, the details of which are not remembered, provide for the intuitive judgment of experts upon which we all rely so heavily.) The weight and value of the collective experiences of many crews can be brought to bear, constructively, in the design process, even before we start bending metal; (3) A base line for the selected approach against which all future variations/compromises can be examined for effects upon mission performance and quantified; (4) A base for developing and extending this approach for assessing system and mission effectiveness into more sophisticated and sensitive areas wherein all relevant dynamics and functions can be examined (simulation and flight test); (5) Geometry (crew position, windows, panels, ingress and egress can be examined in context.)

Component Development and Test (Research, Development).--In the design of instruments, display content and format are crucial factors in the ultimate performance as is the accuracy, response, repeatability, etc. of the mechanism. Bench testing of the mechanism, in a systems context is widely used (but really in a limited systems context). The equivalent for display content and format has not reached the same level of maturity. Part task simulation, naive subjects, even experienced subjects, left us with an unsatisfied feeling. General purpose digital computers and our crew station mockup provided us with the means. The Design Scenario and our mock flights provided the scheme. Using laboratory equipment and general purpose CRT's, a proposed instrument could be represented in proper context in the cockpit and the experiments could be performed in the context of the mission to be performed. What we were able to do is not part task but full task, part mission. The segment of mission selected permitted exercising the display to the full extent necessary, with the crew and in the context of associated work and distractions (or at least with a higher degree of fidelity than otherwise used). The cost for such a setup is, of course, substantially higher than part task simulation. The difference in quality does, in our opinion, justify the time and cost. However, once in place the cost and time per subsequent experiment becomes highly cost effective and time efficient compared to conventional laboratory approaches while retaining the much higher level of value (Ref. 8).

Thus we have established a design method which can continually expose the effect of subsystem change and compromise upon the total system performance.

An extremely important factor is that system/mission compromises are taking place, reflecting adjustments to the myriad of subsystem changes. Now with this scheme of a design mission the changes can be readily reflected down to the component design level in a manner which permits the the designer to quantify the impact upon his own design. While control from a system level upon component details is implied, it is really control of the detail structuring of the problem and criteria, leaving considerable freedom for the individual engineers and scientists in exercising their own judgment for producing the most suitable product.

Crew System Design.--All design can be improved by an iterative approach (each mistake discovered can be corrected in the next attempt). In the crew system case, it is hoped that each iteration will proceed to a greater level of detail and involve fewer corrections to the thread of the prior design. As the design of components and subsystems progresses, the scheme of assessing mission effectiveness and system suitability must also progress to deal with the increasing depth of detail and breadth of concern. The individuals most able to do this are those steeped in all aspects of the mission performance, operational employment, system functioning. Of course this has been the thrust of training and responsibility of the core group. They must insure that mission scenario details are expanded upon and validated.

Details of system functioning must progress from abstract conception to the hard realities of what the equipment and crew can do and what the real world exposure is going to bring in terms of geographic environment, weather environment, threat environment, force structure, operational constraints and economic and political factors and constraints.

The narrative mission description evolves in great detail and many forms. The process of advancing this can be extremely confusing and challenging. It poses considerable demands upon the core group in exercising tact in human relations and challenges the technical breadth and capacity of the core group. The harmonization of the efforts of thousands of diverse personalities in hundreds of locations without face to face contact is one of the most imperative ingredients of a successful weapon system design. We are not assuming any authority for the weapon system design, we are concerned with a subsystem that, in effect, has tentacles into or is affected by every aspect, every facet, of the weapon system design. We must be aware. We must be responsive to all elements of the weapon system if the crew is to be able to demand and get every bit of performance possible from the weapon system.

PROVE

Our ability to learn something useful about the potential value of a crew station design improved with the flying of the paper mockup (a dynamic review). To enhance the learning comparison of subsequent iterations, it was necessary to establish a formalized structure for this review and test. Although almost totally subjective, a degree of quantification is possible through the use of rating scales. The Cooper-Harper

rating scale for handling qualities (Ref. 9) is widely used and accepted. A similar scheme for our interests seemed to work quite well. As you would expect, a questionnaire suitable for standardization doesn't get established on one try. We had to determine what were the meaningful and useful questions to ask. We could and did (still do) use tests of readibility, interpretability, etc., in the individual design efforts. What we needed for the gestalt of the crew system was a test (or battery of tests) which would be sensitive to system performance factors. They should identify and measure factors which designers can respond to in pursuing improvement.

There are several kinds of information which could be useful. (For example, examining each mission task - could it be performed at all - did it strain the capability of the crew? If difficulties were experienced, what was it that contributed most to the difficulties?) The mock mission flight by experienced crews provided to them the necessary stimulus and reminders to permit very substantial contributions along this line - usually in a narrative format - often in debriefing interviews (or bull sessions).

The crew judgment was (and is) based upon their unique experience. We have a comparable situation with respect to experimenters. As they accumulate experience in observing crews, they also develop an "intuitive" ability which differs from that of the crew in that the intuition is derived from observing many subjects as contrasted to the single subject experience of a crew member (at least it is self observation, slightly modified by observation of crew mates).

The use of experimenters' subjective judgment is a relatively new idea and the technique seems to have positive advantages. The initial questionnaires were useful but are still evolving. (Should we call the experimenters second order subjects?)

The data acquired from the crews and experimenters in the role playing exercises with the paper mockup gave us a tremendous lift and sense of progress. We felt as though we were developing more insight into what makes a good operation. A very personal feeling of satisfaction was evoked by the progress in improving the cockpit and the crew performance without addressing the flying task or simulation of the flight control system. This serves to dramatically emphasize the point that over 50% of the workload and challenges upon the crew are tasks other than flying. The flying task is so important that concern with it has tended to obscure the growth in significance and workload of the other crew responsibilities. In the process being discussed, control system teams have been pursuing a parallel track to that of the crew system team - with lots of communication.

With the conclusion of the formal dynamics review (paper mockup phase), the design team had a conceptual design in which they could have a *high degree of confidence*. They were in a position to write, in greater detail, of the characteristics needed and constraints required for each of the cockpit devices and the functioning of the supportive system. If the communication link has been strong and effective, nothing will come as a surprise to all of the affected design groups (comm, nav, fire control,

flight control, instruments, etc.) It is to be hoped that they have had a consultive participation all along. (It's in their own interest to contribute and to get this information.)

The use of a paper mockup does not provide for the kind of numbers so dear to the heart of an engineer. It does provide numbers (subjects, subjective quantification, time durations, errors, etc.) for the psychologist. This is interesting (and appropriate). The emphasis is upon functioning, or functional relations - a description of what ought to be. It provides the boundaries, the scoping necessary for the engineers to ply their trade. It is far different from the conventional use of behavioral scientists (which is frequently for evaluation after the fact of design or to produce generalizable handbook type data.) It's a role not clearly recognized and defined - yet it may be the most significant one.

The completion of the dynamic review of the mockup is as close as we came to a formal completion of the problem definition stage (preliminary investigation). At this point, we have a fair degree of formalization in architecture and in functioning and in partition. The customer has a good appreciation of the planned functioning and capabilities of the weapon system. The various subsystem teams are quite well oriented so as to pursue their individual design concepts to arrive at the equations, the gains, the values, the specificity of how the hardware will be built and what it will do. Breadboard equipment is a possibility but commitment to final fabrication is not. The next level of sophistication in assessment is required. Basically, it is a look at how well all the equations and numbers are going to relate to the functional concepts of the paper mockup stage. In a word - simulation. If mockup was "formative stage" then simulation is "definitive stage."

Simulation.--The Simulation is not just a system assessment effort. It is a family of efforts. The core group interest is in analyzing the system, while the interests of the subsystem teams are in analyzing their own special areas. It's a period of iterative testing. First, the overall, fly the mission and identify weak points or needed subsystem adjustments. Second, engineering employment for each of the subsystems (man-machine, nav, flight, armament, etc.) Third, iterate steps one and two until a satisfied concensus is reached.

Some problems may be taken from the system simulator for intensive experimentation and investigation on smaller, specialized simulation equipment.

If this sounds expensive - believe it. But you have only to do it once to become convinced that it is worth it. AND that it is more cost effective than the past conventions. The most startling thing is that a large cost, heretofore hidden (by being included in larger items), has become identifiable. Once identified, it becomes subject to efforts to make it cost effective. The dollar value sounds large but we made an effort to compare it against the costs of the conventional approach. Considering the cost of corrections normally necessary after building, we estimated, conservatively, that there would be a true improvement of 50% in the cost picture. Unfortunately, management does not normally have prior costs broken out to permit direct comparisons.

It has been out of learning programs such as this that concepts for system growth and new system concepts have evolved (e.g., fire-flight control systems, flight-propulsion control systems, crew adaptive systems).

In the simulation work we strove for fidelity and realism. Many little things that don't impinge upon your consciousness contribute to feelings of realism. Each program which we conducted improved in this respect and in each one we resolved to improve the next. Our preflight planning and briefing conformed to the real operational performance. Flight clothes were used. Cockpit checkout and preparations were as realistic as possible. Background noise was simulated. Radio traffic, static, etc., was as realistic as possible. All possible communication points were "manned" by experimenters. Communication, for example, simulated the effects of a helicopter upon a speaker (he thumped his chest while talking to give the effect). Whether it was the validity of the situation or the observed intent and seriousness of the experimenters to be thorough (a'la the Hartford experiment), we don't know, but the operational crews were very responsive and it worked. Whatever the reason, the continued increases in realism produced an improved situation. Our interest in realism extended to all stations and crew members. For a loadmaster we not only mocked up his station but an entire cargo with lashings and tie downs.

Figure 3. Cargo Compartments (Real and Simulated)

The multiple use of the simulator includes use of it for re-examining crew roles and duties and re-analysis of the scenario based upon measured values.

We had started with a narrative of a scenario that included all mission tasks (the Design Scenario). Using the observations made in similar type flights and with the participation of crews experienced in the mission, a time based description had been devised which included details of functions to be performed (by machine or by man). As the new system evolved we adjusted this to be compatible with the described functioning of the new system. In the initial layouts of the paper mockup we sometimes started from a preferred crew size and crew role statement. In some instances crew size and role was not constrained and then we tried "ranging shots" of high, intermediate and low crew sizes so as to span the probable crew size. The detailed scenarios could be adjusted to assume roles and duties for each of the crew sizes. However, these adjustments were estimates only. We "flew" the estimates to check them out - corrected/adjusted and reflew. For this part of the design effort we needed operational people who participated on a contractual basis. A considerable amount of experienced and qualified judgment was needed to examine and adjust the crew duties and responsibilities. The task required an inordinate amount of details and alternatives to be juggled. Many of the very critical considerations for the process are not to be found documented.

Trial after trial in the mockup led to detail, time based descriptions of the activities of each crew member, the functioning of the equipment and the relation to the mission for each design. Each design included crew size and equipment. The trade offs included changes in crew roles; crew complement; crew size; equipment; automaticity; mission tactics.

The number of variables and the range of effects resulting from changes in just one variable became so great that formalized procedures never got defined.

We had to rely upon the collective judgment of the pilots, engineers, psychologists of the core group to bring the scope of possibilities down to a manageable set of alternatives.

With the determination of specific alternative designs (crew size and role is a design variable), the scenarios could be "firmed up." While the narrative design scenario is always applicable, the details in the design scenario and the bench mark include the unique aspects of each design alternative.

> (During actual practice, an observer might be confused and less than confident. The trial and error design methods of many areas might not instill confidence if observed. In our case, the activity is much more open and observable since a mockup is used. Additionally, many more people feel qualified to speak about the cockpit - it seems like every person in the aviation community feels

qualified as an expert on cockpit matters. This is not a complaint, merely an observation on the degree of attention that cockpit work engenders.)

This activity was a lead-in to the cockpit layout. Of course we started with some hypothetical layouts, but they were trials only, something of substance to allow work to proceed. The determination of specific crew and equipment parameters provides a base against which a specific cockpit design is evolved. This phase draws on additional sets of experts and a whole host of additional tradeoffs. We are allocating space and position to switches, knobs, displays, lights, annunciators - literally hundreds of elements. Sometimes it seems each element has its own champion. We have had meetings with all of these present. Each person to explain the functioning of the device to the others and all to hear the rationale for the design patterns established and the framework (mission/design scenario) for employment. A meeting like that is an impressive experience in human dynamics.

Large group discussions can stimulate thoughts and bring out points that might otherwise be missed. So it was useful to have them once in a while. In our early efforts they were a real adjunct to our learning process. As we learned from them we could incorporate the results into our process and therefore be less dependent upon those kinds of meetings in subsequent programs. (Don't exclude them completely - but one may be all you can stand.) In general, the impact of this experience was to be more explicit in our scenarios and in detailing the functioning of equipment.

This step developed two themes for time based description of the mission: (1) The crew oriented viewpoint - who does what, when, and with what, and (2) the equipment oriented - what is each gadget doing - what's happening in the data flow (it is a data system management orientation). The development of the first is crew dominant while the second is engineer dominant.

This step has gone a long way toward establishing guidelines and constraints for the component people. That's not to imply that they have been idle, waiting for this. Their design work has been progressing in parallel with this activity. They have ascertained many design options and this present activity of the core group provides a firm basis for selection among those design options and guidance for further refinement of the options selected.

Details of the display had been hypothesized. Now a clearly structured situation can be presented. That is, the specifics of a mission task, the information required and the detail decision needed. Maximizing the man-machine relationship can be pursued effectively within this framework. (Past activities frequently looked to maximize man-machine irrespective of mission effects - or with the attitude that "What's good for man-machines is good for the system.")

Part task simulation of full mission activity can be focused upon quite explicit goals. Tailoring of generalized human factors principles to the specifics of this situation is now a practical step.

This just about reaches the limits of utility of the paper mockup. The level being approached in the system design requires more sensitive system tests and more fidelity in representing the system that is to be tested.

This can be an evolutionary type of improvement. For example, in one program we proposed a new combination of nav and comm control. It was an integrated control head. We breadboarded it and put the functioning control head and display units into the paper mockup for "first look" in the system/mission context. Several were tried and the experience stimulated some creative and useful variations.

Where more complex situations existed, full simulation was used. For example, a subsystem involving multipurpose electronic display and multifunction switching for management of weapons stores. Adequate investigation required that the full dynamics of a mission situation be represented. A mission scenario, as I've described it, provided the framework against which to investigate the problem. A fully equipped cab and simulator provided the equipment. Operational crews flew applicable mission segments wherein the total mission situation and loading was presented. This was a full task, part mission experiment. The center of focus was on the design of a specific subsystem, but the framework/structure used provided for the total system context.

The results had face validity for the casual observer and were highly defensible for the more perceptive reviewers.

As our paper mockup phased out, the activity on crew station component design moved toward the climax of detailed design evaluation (at the subsystem level but in a systems related manner).

Naturally enough, a successful and satisfying experience in one program led to repetition and expansion in subsequent programs. Since our organization was R&D we were not committed to production schedules and we were resource limited. For each program there was a prioritization of effort on the basis of advancing understanding and value of results. Consequently, many of the examples, which we have, tend to be from isolated piecemeal programs.

Rising personnel costs raise questions about reducing crew size. Greater and more diverse vehicle and weapon capabilities raise questions about the crew ability to cope and employ. Rising equipment costs and increasing complexity of equipment raise questions about the inclusion of such equipment. In all cases the tradeoff process must look at the effects of any decision upon mission effectiveness. It should provide this opportunity prior to vast expenditures for prototype equipment.

Considerations such as these have led to the need for a more extensive and more rapid expansion of (our activities) this process.

In recent years we've been able to put many of the pieces together into more complete programs (Ref. 10, 11).

It takes a large program to support the subsequent steps in this methodology.

We have followed a theme of development, refinement and increasing detail in describing the design mission (the design scenario, to be used as the bench mark in assessing the effectiveness of proposed systems). While the total system must be represented, the method is sensitive and definitive to variables in the crew system. Representation of a fully functioning system and the ability to fly it against a realistic mission problem requires large scale simulation facilities (or access thereto) for substantial time periods.

So far as procedure is concerned, simulation uses the same basic approach as the paper mockup effort, only it is more complicated and demanding. For our first experience, one of the traumatic adjustments came about because we had equipment and experienced simulation people. The people and equipment had been oriented to flight control problems. The natural thought was to expand that to include some of the subsystems. However, the adjustments were far more significant than mere additions. Gross approximations, so perfectly satisfactory before were not recognized initially as inappropriate. Test sensitivity requirements were drastically different, as were test conditions. The part task aspects of flight control simulation are several orders of magnitude more complex than what is conventionally visualized as part task - so much so that many took to thinking of it as though it were the full thing. In a nutshell, the transition asked was from part task, part mission simulation to full task, full mission simulation.

When discussing the mockup, I referred to it as the "paper" mockup to emphasize that it could be cheap and simple. Over the years we have actually used many variations from paper (literally) to rather substantial metal structures. "Foam core" seems to be a useful medium for the initial trials.

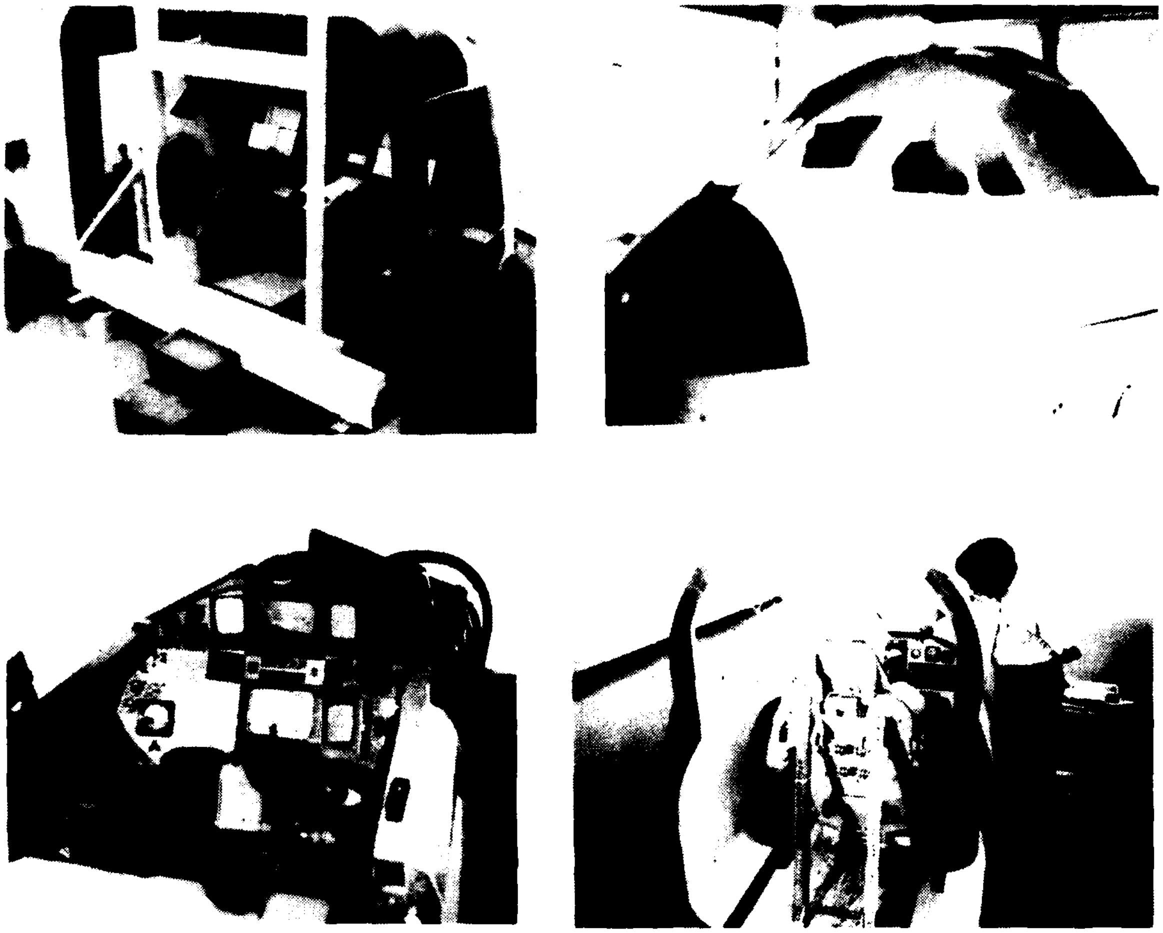


Figure 4. Mockups

We have substantial shells for different classes and sizes of vehicles in which we can readily install foam core panels and pictures. As time passes and designs are made more firm, the foam core and paste ups can be replaced with more durable structures and devices. The mockup can, therefore, grow. It is possible for it to be used as the simulator cab if the shell and basic structure are suitable.

As time passed we felt the need to identify the level of sophistication of the cabs used. We established three levels (Class A, B, C) (Appendix A). The simplest could suffice for the initial work, but in the final stages of design and of evaluation many features had to be precisely simulated and controlled.

SECTION II

OVERVIEW

Chapter I reviewed some of the history, rationale and experiences leading to our present views of an appropriate methodology for crew system design, test and evaluation. It is the intent from this point to discuss the pattern of activities, the dependent relationships, the time relationships and significant ramifications and relations beyond the crew system domain.

It's been said before, but can't be repeated too often. The work does not fit into the neat independent blocks. We use block diagrams as an inadequate tool for communication. It helps to focus on a point we wish to draw to your attention. We use lines to connect blocks for purposes of showing dependent relationships and the logic of process. In reality the interflow exists universally. A real diagram would probably be like looking at a huge platter of spaghetti and meat sauce. (For those of you who understand this point, please excuse the exhortation. Due to the difficulties of communication, we have found it necessary to belabor this again and again.)

The process follows that very basic idea of Define the Problem, Develop a Solution and Prove the Solution. We have found it convenient to use this division in discussions because it conforms to significant changes that actually take place. The nature of the work changes, the skill requirements change, the magnitudes of cost and manhours involved change in accordance with these divisions. Even the time factors change.

It is useful to note that starting a program such as this is not a commitment to the total program. Each of the three basic phases can establish plateaus where program termination will not be harmful in the sense of wasted expense and effort. Each phase provides a milestone worthy of achievement.

Another item to be noted is the role of test and evaluation. A structure for testing is an implicit part of the methodology and the test/evaluation process. It starts on DAY ONE along with the technical effort. It is not just an after the fact process.

Testing requires a structured plan for the acquisition of data describing the characteristics and behavior of a component, a subsystem or a system. Likewise, evaluation requires a structured plan for the determination of the criteria against which the test data will be assessed. Each phase of this program requires validation (test, evaluation and approval), starting with the initial statement of the problem. As a program progresses tests will accumulate data on the components, the subsystem and on the total system. All of the tests provided data for the final decision process. There is a pattern to effective testing so that the accumulation can contribute effectively to the final validation process.

DEFINE THE PROBLEM

The starting point is identified in our diagram as the "SON" (Statement of Need). It is generally understood that such a formal statement should provide as much leeway as possible for the vehicle designers who will compete. The objective is to provide the greatest opportunity for creativity and innovation in advancing our capabilities. There IS a need, an anticipated or actual deficiency in our force capabilities. It is possible that in some plant or organization an idea exists that would merit a totally different approach to dealing with the problem. However, lacking this, the originators do have in mind a way to deal with the need. The SON is a starting point for exploring ideas, not necessarily the point for starting development. In the crew systems arena we are not going to advance capability until we know the challenges. This is perhaps where the real distinction between it and other subsystems exist. Radio, navigation, radar, etc., are all physical areas. The challenge to expanding their technology is definable in the terms of physical science, generally, irrespective of the application. In the life science area the challenge is to know and define the behavioral, physiological and psychological capabilities and limitations of a biological element.

The crew systems challenge is how to use all of this knowledge for the successful employment of warfare systems. The challenge is more in the intellectual, cognitive functioning of a complex of men and machine doing a job. A job where gross performance characteristics are known but detail perturbations can not always be predicted. The intangible feeling is what gets you. You have to ask about a lot of things before you can know that some particular piece of info really isn't needed.

The SON is the trigger to cause people to look for improved airframe and propulsion, improved ordnance, etc., etc. It should also be the trigger to look for improvements in the total mission performances through proper matching and use of crew and equipment.

The problem must be explored from the perspective of the crew and the intentions of the warfare planners.

There are several boxes used, all to the effect of understanding the problem in breadth and depth so as to BE in a position to be creative and responsive in crew system design. The milieu for airframe design is the atmosphere, the milieu for radio and radar is the electromagnetic environment, the milieu for crew systems is the mission. It is not a basic physical condition of nature subject only to the laws of nature. It is an artifact whose characteristics are subject to the whims of man (of course within the laws of nature).

Because of this difference, exploring the problem is a search for things (details, data) that may be of value. Because of its nature it is not necessarily responsive to the same questions and measurements each time around. Efficiency of interview needs a structure but we can't be assured the structure is appropriate for the next interview.

Face to face interviews at all levels of the customer organization, from the crew to the command level is desirable. Participation in the current equivalent of the desired operations is valuable. All with the objective of getting a gut feel for all desires of the customer and all ramifications of the problem.

Understanding the problem in infinite detail is 40% of the challenge in building a system. Knowing what constitutes the real scope of the problem is 50%.

We have said a test is a process for getting data. The test technique in this instance is the interview. The data must be organized and validated ("Is this what you want?") to insure that subsequent efforts are properly pointed.

SOLVE

There is a finite indication on the chart for transition from Define to Solve. It's really a change in tempo and emphasis. Tentative designs are useful in exploring the problem. They help uncover miscues in communication. They may reveal to the initiator that the original request had as implied needs, features not really necessary. The design may surface discussion of needs or constraints not previously mentioned.

So far as the Solve orientation goes, the checking of the trial designs helps to steer the design themes into acceptable channels.

Initial design schemes are merely grossly simplified discussions of systems concepts. As the requestor and the responder progress into a satisfactory theme the approach can be partitioned and teams initiated for these partitions. In each team an action takes place equivalent to that which the requestor responder went through. Trial designs for each of the teams checked back against the systems concept of the responder (and core group).

Thus the activity grows and branches but always retains a close check to the overall theme of the design. This branching growth draws in more people and proceeds to levels of detail necessary for finalizing designs. During this period it is to be expected that most of the traditional measurement techniques available will be used by the designers. The data derived is used by the individual designers but must also be retained for integrating into an overall package describing the total system.

As these individual designs evolve they must be fit into their appropriate role in the overall system design. A paper/cardboard mockup provides a step in fitting the pieces together. A role playing scenario which has also been evolving in this phase provides the structure to allow real crews to assess the designs in terms of their collective utility as a system to address the original mission problem. This mockup activity really represents the transition stage from Solve to Prove.

The first activities with the paper mockup are as a design tool. As designs become more firm, its use becomes more appropriate to a gross evaluation of the system design (including crew roles and duties, operational employment, as well as the hardware features). A seemingly contradictory condition is moving into the Prove mode based upon paper design. That's not strictly true, the component design will have moved through breadboard, even brassboard by this point with the design supported by all the normal physical testing. The paper mockup will have been upgraded to highly accurate drawings, pictures or, in some cases, the breadboard equipment.

The dynamic interaction of all the components of the system get looked at in their total interplay first by means of simulation and finally by flight test.

PROVE

The Prove phase involves two orientations: (1) Componentry - This involves the conventional approaches wherein components and subsystems have been subjected to batteries of tests to determine compliance with industry standards and specifications, to measure output, input and performance, to analyze reliability and survivability, etc. (2) Systems - This is the unique consideration which is being advanced by this report. It is the concern with the effectiveness of the crew, the vehicle and the subsystems when applied to the mission problems in an operational context.

Componentry.--The testing of the components and subsystems has been been a part of the development process. Large quantities of data have been amassed on the physical and behavioral aspects of these items. Each has, presumably, satisfied the respective development organizations. The final approval and acceptance, however, should provide for collective assessment. This final assessment is to be accomplished by a team of specialists representing such areas as: Logistics, Maintenance, Training, Computer Science, Human Factors, Electronic Warfare, and the various specialties involved (e.g., Avionics, Flight Control, Propulsion, Armament, etc.)

This team is to be provided with: briefings on the equipment design and the rationale for the design, all substantiating data, and the opportunity to examine the equipment. An objective is to make a collective judgment with regard to an inordinately large mass of data. The team will require a substantial amount of time and a mechanism for summarizing their judgments.

The mechanism presently devised is the use of "PHYSICAL ASSESSMENT" forms (Appendix C). The form provides, to each expert, the capability to express a degree of satisfaction or concern for each of several topics. The resultant accumulation of these forms allow for a high degree of confidence by the final decision makers in accepting or rejecting a specific design.

Systems.--The system testing has as its objective a performance capability assessment of the system as operated by the crew in the performance of the missions. The Design Scenario is the standardized guideline to the test procedure. The Crew Station simulations, along with supporting equipment provide the mechanism for the testing. The process, as previously discussed, is to have subject crews "fly" the missions. Subjective and objective data is to be obtained from these "flights." As in the case of the Componentry Test, the data must be reduced in a manner which allows for informed and confident judgment by the decision makers. In this instance, the team assessment is rendered by subject crews and by experimenters using "Performance Assessment" forms (Appendix D).

The system test has three levels of sophistication: (1) Mockup, (2) Simulation, (3) Flight test, providing for system oriented responsiveness in abbreviated programs as well as a cost-conscious screening approach in a full program. The Mockup test, the most economical, can be used at an early stage to screen out the most unsuitable designs. The Mockup equipment can be upgraded for use in the next level, simulation. The Simulation Test can be regarded as the pivotal test in that it exercises all features of the system and conditions of the problem. In many cases it can suffice for the final decision making on acceptance of a system design. The Flight Test level of test provides the highest level of confidence in the decision process and is, of course, the most extensive and the most expensive.

The Mockup Test--as previously discussed was used as a design tool for continual check as the component designs progressed and, in many instances were upgraded to breadboards in the mockup. The change from a design tool to systems evaluation is in the scope and character of experiment being applied in the mockup. For design purposes few subjects and limited treatment are satisfactory. For system evaluation considerable care is required determining the number of subjects required and in the selection of the subjects. Additionally, for system evaluation is the need to examine the full range of the Design Scenario with care and formality.

The Simulation Test--has the objective of considering the effects the aggregate performance of the system components in a realistic representation of the design mission scenario. (The simplest and most economical technique of mockup was used as a first screening of the totality of a proposed design. We assume that there will be bugs uncovered. Minor ones can be corrected before moving on to the second level of sophistication, the simulation.) Simulation brings a very dramatic increase in completeness and realism. To the crew it appears as a completely operational system with all elements functioning. The crew does not have to, themselves, simulate workload and activity. The simulation set up provides for the processing of considerable amounts of objective measurements on the performance. The capability to screen out undesirable qualities is vastly improved. The sensitivity creates the effect of a very fine screening device as compared to the mockup device. Naturally the costs of manpower, hardware and the duration are also vastly increased over the mockup stage. Correction of any deficiency after simulation is therefore substantially greater. There have been greater investments into

hardware and software which may be wasted. That consideration has made us particularly aware of the value of the Mockup stage. Recovery after the mockup stage is not nearly as expensive.

Even with all the care that can be mustered, it is to be expected that needed or desired changes will be identified in the Simulation phase. The system checks throughout the design process and the Mockup phase of Proving should have resulted in eliminating the need for the more costly changes.

When the simulation experience and data has been digested, work progresses to the flight test. Flight test is really "proof of the pudding." There are two important considerations: (1) Simulation never provides 100% fidelity. Therefore, the assurance provided cannot be 100%, perhaps 99 but not 100. (2) Mating most of the components and operating them as a system can (and should) be done on a hot bench. Mating all of the components and subjecting them, as a system, to the operational environment can only occur in an aircraft.

Flight Test--provides the final "proof of the pudding" demonstration of the effectiveness of the design effort and perhaps more importantly it provides for the final fine tuning (of gains) as real flight is experienced. It is not performed as a screening function, it is not done with the objective of catching flaws. It will, of course, but if it does then there was a failure of prior screening efforts.

Flight test is the victory flourish of the design effort, the icing on the cake, the final spit and polish.

Lest we create a wrong impression - the flight test referred to here is the final evaluation of the Crew System. There most surely has been flight test as a part of the design process for many of the subsystem problems.

Flight test is expensive. However, the test vehicle and ground support is provided for purposes of airframe, propulsion and flight control investigations. Expansion to include crew systems is then not as great an economic burden as it would be if conducted as an independent test.

SECTION III

THE PROCESS

Within this chapter are listed the steps in a sequential manner and with some explanatory remarks. Since there is parallel activity, I have used a diagram to show the relationships.

It is important to note that an objective in this document is to show an orderly and logical relationship of activities stemming from the conception of need to production design. Some of the activities are traditional, some are new proposals, none are the exclusive responsibility of one organizational element. The logic of ordering is responsive to the needs of Crew System Design.

DEFINE THE PROBLEM

1. Establish Mission Concept

The design and development of a warfare system (weapon system) starts with the concept of a mission. Ordinarily this is the result of continuing effort by Requirements elements in the respective Commands and at Hqs. USAF. One or more documents are prepared to provide formal recognition of the need and to cause responsive activities to begin. Some titles and terms which have been used are Required Operational Capability (ROC), General Operational Requirement (GOR), Statement of Need (SON).

2. Develop General Operations Plan

The General operations plan will state how the mission is to be accomplished. It will consider manpower, geography, logistics, threat, objective and all of the factors related to a military operation. Various documents are produced in this process and they can be updated as new information is processed. This activity can result in revising or reissuing the documents of Step 1.

3. Develop a Trial Problem Statement

Based upon data available from Steps 1 and 2, and further augmented by interviews, a document is prepared to describe the problem. The document is to provide as much detail as can be elicited from documents and interviews. Where voids or uncertainties exist, assumptions will be used based upon "best guess" projections so as to make the problem statement complete.

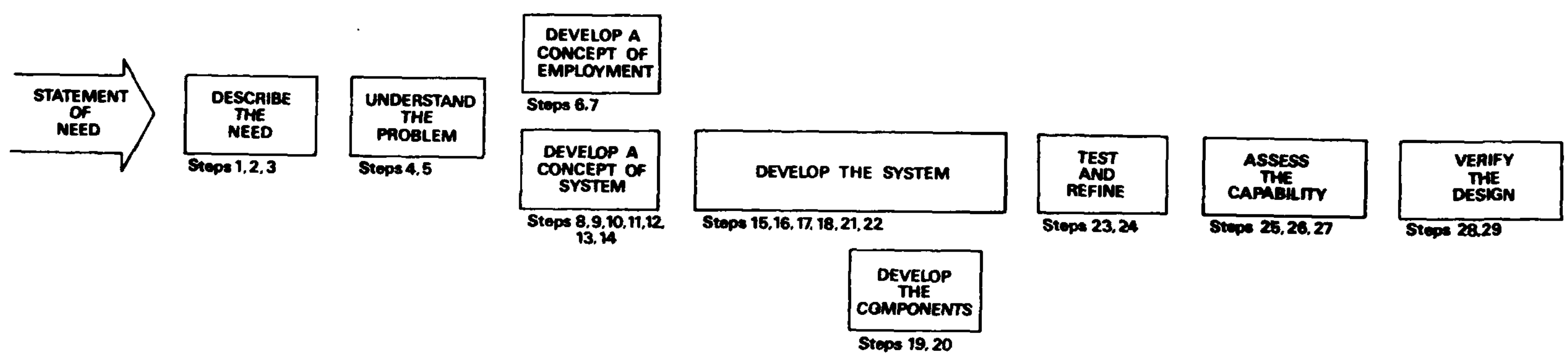


Figure 5. Flow Diagram

4. Field Studies

An on-site observation and interview period. Key members of the crew system design team (core group) visit operational sites where the current equivalent of the desired operations are being practiced. This should be an indepth experience, including participation in the missions if practical. Extensive contact is desirable with operational people at all levels of experience and responsibility.

5. Restatement of the Problem and Requirements

Prepared by the core group, this document provides a substantial expansion of the details over that produced in Step 3. It must make clear all of the implied requirements. These are the requirements that come into being as a result of the originally stated need. They also include those derived by observation and analysis during the Field Studies (Step 4) and which were not explicitly stated by the requestors.

6. Mission Narrative

Sufficient substance (albeit conceptual) exists to describe, in narrative form, the employment of this vehicle in the accomplishment of the mission objectives. This draws heavily upon the cumulative data and experiences of Steps 2 and 4.

This step is, in effect, a validation point for the core group. It is a means to affirm with the operational people and technical consultants that there is adequate mutual understanding of the problem, of the ramifications of the problem and of the probable solution.

7. Detail Mission Profiles and Environments

With acceptance and approval of the Narrative (Step 6), detailing and first pass quantified descriptions are prepared. These details and descriptions include Altitude/Time profiles, Environment (natural, electromagnetic, threat, operational), Speed/distance. This information in company with the latest documentation of System Concept and Mission Narrative sets initial goals and constraints for the subsystem design teams.

8. System Concept

Following a common understanding and acceptance of the Restatement (Step 5) by the Operational people and the design team, a concept or concepts of systems capable of satisfying the need are devised and described.

> It is to be expected that an improvement in communication between designers and users will result, particularly with regard to implied requirements and prior unstated assumptions. Consequently there could be one or more iterations of Steps 5 and 6.

9. Systems Architecture

The total development can be parcelled out among many specialty groups, large and small. Airframe and propulsion are the most obvious and by their size and nature tend to be independent. Avionics and Life Support are the other major divisions which seem to be traditional.

Within all of these there are factors related to crew system design and which, through their impact upon the crew system, affect total system capability, performance and mission effectiveness.

The question to be dealt with here is the determination of partitioning and structure that is (1) most appropriate to effective employment of the weapon system by the crew, (2) most responsive to current technology, (3) most suitable for survivability, reliability and maintenance, and (4) most efficient for design and production.

Traditionally communications, navigation, fire control, and flight control have been independent systems within the skin of the Weapons System airframe. They should not be selected as work divisions by virtue of tradition but only if that is compatible with the best interests of the system. Sensors, Computers and Actuators is an alternative division (not seriously proposed but used to illustrate).

Crew systems cannot control the actual assignments but can, for their own use, redescribe what actually takes place. On paper and in simulation the activities can be described with divisions appropriate to the interests of flight control.

This is not an exercise in futility for it is a means to pursue a logical crew system development to a conclusion and then be able to derive the requirements which must be imposed upon the actual subsystems. It is a somewhat artificial situation for awhile but it provides the means for crew systems designers to get a handle on the somewhat vague tentacles and scope of their system.

This may not be the best way but it is a practical way for crew systems to proceed under the present organizational structures.

The difference between the hypothesized and the real will probably be subtle and in degree only. But the difference will be significant to crew systems and to future programs (a trend setter).

Within the cockpit and life support areas the architectural considerations become more authoritative and the division can be explicitly responsive to optimal system design.

10. Establish Probable Nature of the Vehicle

Using the consultative services of the airframe and propulsion people, an early approximation can be established to describe the likely configuration and performance characteristics of the vehicle. This will require that the crew systems (core group) commit to first guesses on such things as crew size, position and external vision. (If crew size

is to be determined then parallel designs for the candidate numbers may be necessary.) If the crew systems activity gets started soon enough and proceeds through one quick design iteration (based upon many gross assumptions) they will be in a position to give substantive input on the cockpit considerations into the airframe design. It is to be hoped therefore that all of the preceding steps and some of the subsequent ones can be pursued on a quick and dirty basis prior to the real formalization of a program and airframe design. Some answers are needed before you start. Therefore the R&D community should be providing this initial quick pass activity based upon their best guesses as to the direction of future system programs. It appears to be the only way to provide for truly adequate cockpit consideration in vehicle design.

11. Time Based Analysis of Mission Management

This will be the first of many iterations wherein the mission is examined moment by moment to ascertain and describe the control actions needed in order to accomplish the mission. This must be presented on a time base. This, in turn, must be analyzed against the hypothesized system to determine information requirements that are necessary to effect the defined control. The requirements for mission management strongly affect the functional system definition.

The first pass is an idealized situation and deals in abstract considerations. It does not yet cover the specifics of crew roles or monitoring of equipment.

In this instance a system is to move through space under generally defined constraints (altitude, speed, and distance plots), do a job, and return.

12. Technology Assessment

It is to be assumed that all technology groups remain knowledgeable about the state-of-the-art (SOA) and about R&D programs which are to advance the SOA. This step requires the combining of the system needs with the technical potentials. It is a challenge to the core group in coordination and assimilation. Their first pass description of how the system might function and of what it should consist receives its first serious challenge as the many technical specialists are consulted to pin down, refine and define in some detail the real story. This can produce an interation or refinement of the Systems Structure (9) or even a change in the Systems Concept (8) which would require review and changes in all intermediate steps.

13. Time Based Analysis of System Control

Details of the probable system are beginning to crystallize. This "probable" system can be analyzed against the time based mission management description. The objective is to translate the mission management needs into the requirements to be imposed upon the subsystems.

the output will be a time based description of the mission wherein the detailed control functions and information needs are non-specific in terms of what each subsystem can or should do.

14. Develop Specific Subsystem Criteria

For each identified subsystem develop a trial specification couched in terms of required performance and detailing criteria to be met. This is a joint effort between the core group and the respective design teams. The requirements and criteria are to reflect the data derived in the preceding time line analysis as tempered by the design team's assessment of technical possibilities. Environmental conditions are derived from (7) mission profile and environment and the general expertise of the design teams jointly agreed to by the core group and the respective design teams.

15. Develop Trial Cockpit Geometry

Using handbook type data, layout the geometrical features of the required crew stations. This effort must be responsive to crew size and relative positions as proposed by the design concept(s) first introduced in System Concepts (8) and expanded upon through Systems Architecture (9) and Probable Nature of Vehicle (10). Specific concerns to be addressed include external visibility, egress/ingress (normal and emergency), reach and vision zones, display and control surfaces, seats, beds, galley's and relief facilities.

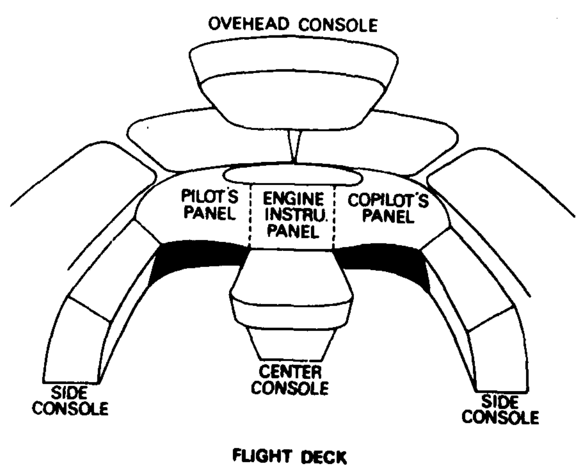


Figure 6. Cockpit Geometry

16. Develop Trial Control/Display Layout

Based upon the general awareness of mission and goals and supported by the detail analysis (11) and (13) a first pass design layout is developed to show groupings and locations of necessary controls and displays. This first pass is more an allocation of space and location and reflects a first approximation of roles and responsibilities of crew members. Details of how to display the data and how to effect the control will be in a later iteration.

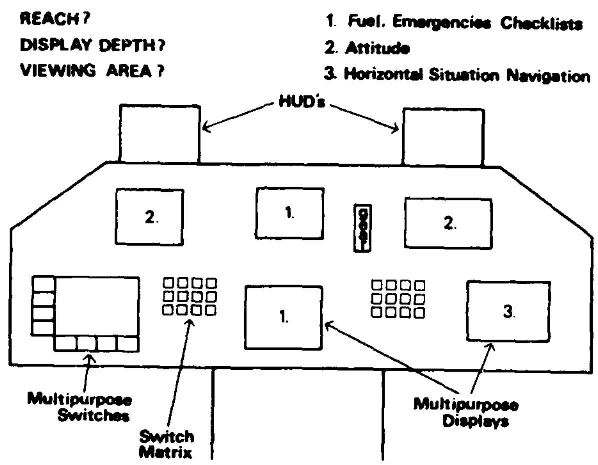


Figure 7. Trial C/D Layout

17. Integrate Crew Station Geometry and Control/Display Functions

Each of the prior steps had as their prime constraints, satisfying the developed criteria and satisfying the general norms of technology. Overlaying the control/display panels onto the geometry is not likely to be easy. Substantial amounts of cut/fit, trial/error tradeoffs will require expert judgment to achieve reasonable integration of the two areas. There are two distinct and sometimes contradictory thrusts in these two areas and in general there will be designers for each area. For this reason they are shown as two blocks. In actual practice the teams will blend and all three boxes will be encompassed as one activity examining and trying multiple options.

18. Identify and Initiate Subset Designs

The control and display needs as developed and defined in the analysis of mission management (11) and system control (13) can be clumped (grouped) according to some logic. It is incumbent upon the crew system (core team) to establish the general scheme, define the groupings and establish the guidance applicable to the grouping (e.g.,[a] copilot must be able to take over pilot duties or [b] no copilot capability, the second person will be devoted to countermeasures or [c] the copilot position will be prime for flying the aircraft and the pilot position will be prime for strike force management). This grouping effort is to be responsive to the general theme agreed to through Steps 1 to 5. It must also include intuitive judgments as workload and performance capabilities of the crew members. (Two thrusts come from this: [1] the roles and duties, [2] instrument developments. In the second, displays and controls are worked up and formats devised. Experiments optimize the format, the control, their interaction and then their interface in the system. In the last case the role/function developments must be accurately reflected in the experimental design.)

19. Control/Display Conception

At this stage of the program, the crew system designers are finally well steeped in the problems. They should have a good awareness of needs and limits and all the ramifications of time, cost, sophistication. It is well to note that there is NO process wherein every step can be in accordance with cookbook instructions and produce innovative results.

This is one point where creativity can break forth.

The program has provided a thorough grounding in the problem, has provided access to resources, has provided opportunity, has provided stimulation - about all that can be done to provide for creativity.

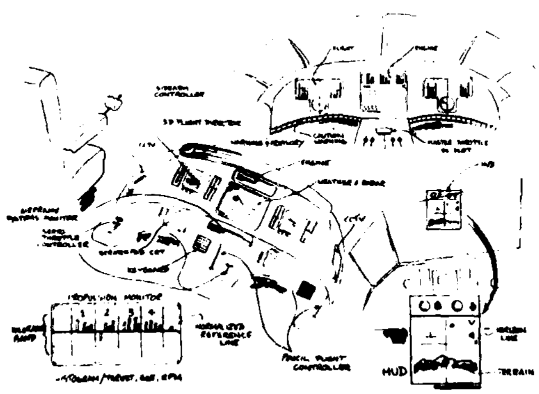


Figure 8. C/D Conception

New displays, new combinations, wild ideas can surface and be examined. It's a fun period. Paper, picture, crayon and cardboard are the tools. Paper panel mockups are useful.

The output is a graphic and written description of a design concept for the details of displaying information, how it is to be used, by who, and what control actions are to be effected, by what means, by what member, and when.

20. Subset Design

This is subservient to crew system design. It is not, in itself, crew system design. For simplified discussion only one is depicted. There will be many. Representative titles might be stores management, flight director, HUD, propulsion instruments, fuel management, energy management or they might be new groupings not previously considered. The design process includes determination of appropriate data source(s), necessary data manipulation, form and format of display, form and function of controls, packaging, calibration, test/monitoring, etc., etc. The design (or selection) of the circuitry and hardware is an engineering job. The design (or selection) of the display and of the shape and functioning of the control is a human factors job. Thus, even the design of a single instrument is subject to the team approach. Laboratory and bench tests are to be employed (as is done) conventionally for measuring such characteristics as weight, volume, power consumption, accuracy, repeatability, response frequency, RMI, discriminability, readability, interpretability, break out force, throw distance, mechanical force requirements, and on and on. In other words, all of the normal design testing is to be done at the normal stage in the development. THE DATA IS TO BE RETAINED FOR USE IN SYSTEM ASSESSMENT.

In addition to the above there must be a continuing procedure of checks to assure compatibility in the system context. Engineering concerns would be grounds, signal levels, form factor of signals, analog/digital. Human factors concerns would be standardized symbols, direction of motion, use of color, use of sound, shape coding.

This subject must be tested in the context in which it is to be used. This will require representation of the circumstances of use, the surround, the dynamics, the crew.

(The subset designers must be prepared for additional inputs which emenate from system considerations - these could be changes in display/function.)

21. Crew Stations Mockup

A mockup (or mockups) is prepared of the crew station(s). It should be simple and inexpensive. Form core has been quite useful for this purpose. The initial mockup should provide for all control and display surfaces in the approximate dimensions and relations.

The controls and displays can be represented by pencil sketches. This provides the means for the designers to visualize the functioning (in a crude or gross way) of the crew station(s) as they review the needs by means of the design scenario.

This first interaction relies totally upon the subjective judgment of the core group.

> There is (or can be) a considerable amount of interchange as alternatives and tradeoffs are considered. This would be among the blocks 15 through 21 and among all of the subset designers with the crew system designers.

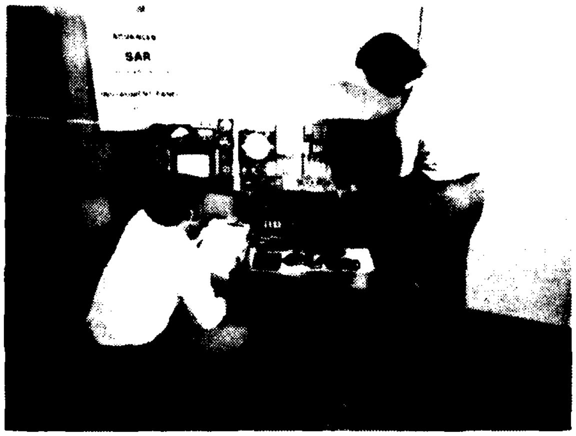


Figure 9. Simple Mockup

22. Crew Station Design - Second Level

When the subset design teams have formulated their approaches, all of the bits and pieces should be put forth in a second level mockup. This can be foam core but should be dimensionally correct. Seats, instruments, controls, etc., should also be represented with dimensional fidelity. Pen and pencil sketches can still be used to present display and format features.

With this structure the first dynamic review can be undertaken.

Figure 10. Crew Station Mockup

23. First Look

This is an opportunity for the "core group" to get a first look at the design concepts as an emerging system design. It is a "Milestone," a place to stop, take a breather and say, "Where are we? How's it going?"

A representative crew is assigned to role play the respective positions. These may be the "core group" themselves. The design scenario provides the pattern to be used in this role playing. The core group and/or representatives from the subset teams can observe. Subjective judgment is called for from the crew subjects and all observers. The task is to stimulate the flying of a mission and to observe, critically, the elements, the interrelationships, the proposed functioning in relation to the crew roles and mission accomplishment.

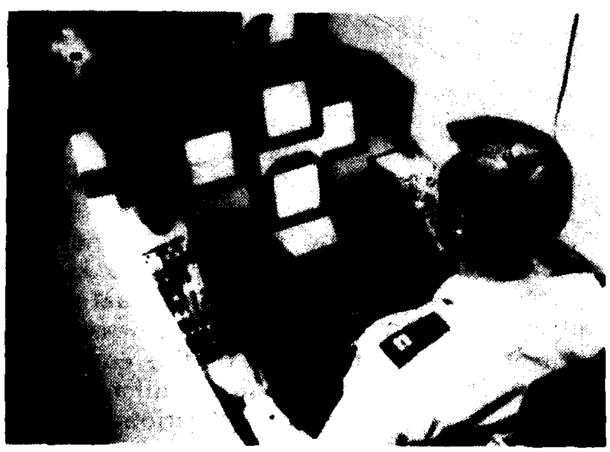


Figure 11. "First Look" Mockup

Since this is a first look at a representation of the system, it is to be expected that a substantial number of needed adjustments to the design will be identified. Tape recording or video recording of the experience and the discussions that develop during the role playing may be quite useful in retaining all reactions and in reconstructing the context in which an observation was made. The astute core group will do this themselves before outsiders have a chance to critique the setup. Despite exhaustive care and analysis, mistakes can happen. In a system of this complexity, with many participants and with many intangibles you can have a 99% probability that an oversight will occur that will be labeled "stupid." Of course, that is why there are internal design reviews.

If this first look identifies the need for substantial adjustment, several steps may need to be repeated.

24. First Look Fixit

In any event there is almost a certainty that some changes will be needed. These could be in roles, responsibilities, timing, geometry, location of a switch, etc. Most will be items which would not have been observable except for the dynamic role playing. With a foam core and paper mockup and typewritten scripts, you're in good shape. The changes will involve a few manhours and very little hardware costs.

> This is a truly significant point. The alternative, with which we have lived, is to discover these anomalies in the preproduction aircraft, or later. Consequently, there was a fortune to be spent or a mission capability compromise to be made.

25. Dynamic Review

The "proof of the pudding" was in the flying of a design. General Boyd advocated "Fly before you buy," in the same vein. In some respects we can consider the dynamic review as "proof of the pudding" with regard to conceptualization. I regard this as the MOST significant test of all. If the concept is good, then all subsequent problems are within our capability to handle. Care and good engineering can do it from this point on.

For a dynamic review a formal process is required. As in Step 23, it involves role playing and simulation of the mission. Recognizing that the mockup is foam core, cardboard and static, it is nevertheless, an objective to be as realistic as possible. The point to keep in mind is that we want to obtain, in the minds of the subject evaluators, sufficient understanding and visualization for purposes of valid assessment. The use of props and mnemonics as an aid or stimulant to the cognitive and visualization process has long been recognized. We wish to capitalize upon it. The subject selection is very significant. Operational crews who have had experience in the proposed missions are most suitable for assessment of probable effectiveness. Low experience crews are candidates to consider

the problems of learning and adaptability. Our interest is to have a sufficient number of subjects so as to safely project that the results are representative of how the total force would react to the production design in normal service. The determination of a suitable number of subjects or subject crews will probably still be debated by learned experimentalists as the earth turns to ashes. There is no absolute answer. In my opinion, it cannot be less than 10 complete crews, representing high, medium and low experience levels.

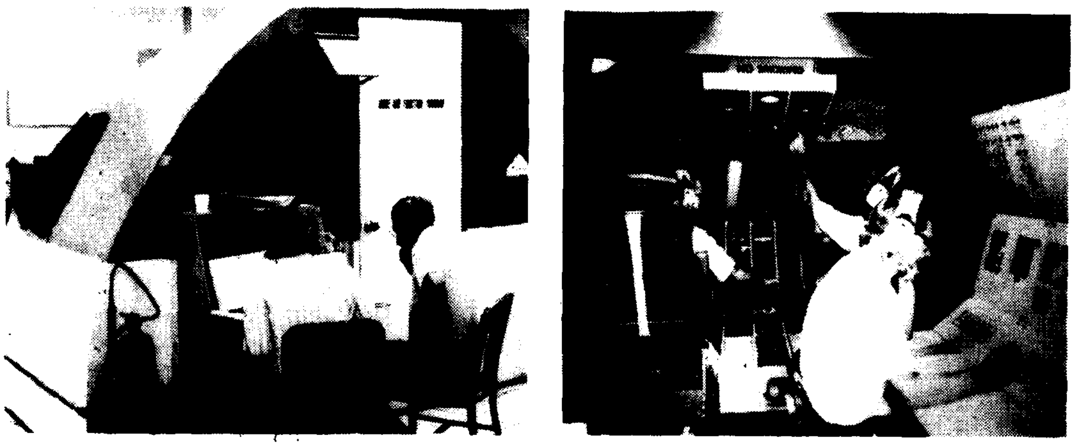


Figure 12. Advanced Mockup

The process is to, as realistically as possible, brief the crew on the mission (design mission), send them to their crew stations in the vehicle (mockup), fly the mission (via the role playing scripts), and conduct a normal mission debriefing. Of course, we have to look for measurements, primarily we are relying upon the expertise of the high experience crews for judgment about the effectiveness of the design for the mission. The low experience crews will tell us something about how difficult it is to learn to use this system. While some techniques, such as time estimation, might be used to anticipate workload, the primary reliance is the subjective opinion of the crew members. Questionnaires (as illustrated in Appendix B) can explore their opinions on the effectiveness and appropriateness of the design for the various mission segments.

> The flying qualities, which traditionally are of great concern, are ignored - not because of the inadequacies of the mockup but rather because the maturity of flight control science has removed this hurdle. We can assume that the flying qualities will be satisfactory.

I strongly recommend that a two step debriefing of the experiment be used. Step one is the formalized questionnaires. Step two is an informal gathering of the participants in a relaxed atmosphere to talk of the things which attracted their attention and interest.

26. Digest and Assimilate

When the dynamic review is done, a normal step might be to organize the data obtained and document it. I call this digest and assimilate because in terms of advancing the system you must get the feel for the WHY of the comments. If there are critical comments you either did not do a good design or you did not have adequate understanding of the problem (or both). You must (1) take the comments and relate them to the problem definition, (2) modify the system concept to take into account the expanded (more detailed) problem description, and (3) adjust the design.

27. Redesign

The development process for the subsystems has been progressing and it is to be hoped that the revelations of the Dynamic Review (25) have not disrupted them excessively. It is possible, even probable, that there will be feedback that has an effect upon design. This, of course, can apply to any or all subsystems. The change may be relocation of a switch on the panel or the redesign of a switching network. Unless there has been a gross fault in the problem definition of the earlier stages, the design adjustments are likely to be relatively small in engineering terms, perhaps only cosmetic.

> In some respects, it is downhill from here. The important and costly decisions are made. Subsequent efforts are channeled as a result of this milestone. (They could still be costly but are now, in effect, preordained.)
>
> The real significance is that KNOWLEDGEABLE DECISION MAKING took place before the expenditures for prototype (or even brassboard) equipment. Not a best guess but a decision based upon substantive understanding and assessment.

PROVE

28. Simulation

Simulation has long been a part of the development process for stability augmentation and flight control. The equations for the aircraft and the proposed control systems are available as are the computers and cockpit. Our simulation needs can be readily appended to this simulator with benefits to the concerned subsystems as well as utility for the crew system.

The simulation can be viewed as an expansion of the Dynamic Review. As in the dynamic review, an objective is to be as realistic as possible from the observation position of the crew members. From the crew viewpoint, there are two outstanding changes. (1) All of the equipment appears to be functional, and (2) the flying task is realistic.

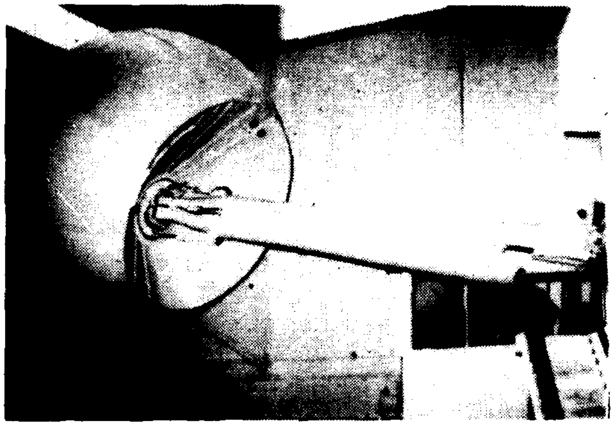


Figure 13. Simulator

Preparation involves support by all of the development teams. Within the cab all instruments, controls, annunciators, switches, etc., must appear as real as production equipment and be functional. Many of the subsystem programs will be able to supply actual aircraft equipment for the crew station installation. In some instances, special fabrication will be required. The associated black boxes for functioning of the equipment may be used or their functioning may be simulated by computers. Considerable attention to detail is necessary to provide for a high degree of realism. Examples include: intercom and radio with audio characteristics equivalent to the planned system; oxygen masks; ash trays; background noise; breakout force and friction for levers and controls. The dynamics of flying require the faithful simulation of the flight control system and the use of the best data on the flight equations of the proposed vehicle. The flight control and propulsion control should include an accurate reproduction of the feel system.

External view and environment.--As a minimum, the simulation should include a visual representation of the real world for low altitude operations such as interdiction, approach and landing. Additionally, it is desirable to control luminance levels so as to approximate flight conditions from full daylight through to overcast night.

Motion.--There are several kinds of motion which impact the crew. It is common practice to simulate onset G's only for flight control investigations due to cost and limitations of simulation equipment. A few long arm simulators can provide short duration G forces. Seldom considered are the vibrations. G forces are significant in their influence upon flight control. However, the total picture for crew systems includes the effects of vibration upon the crew. Vibration can influence readability of displays, actuation of controls, and can contribute to fatigue. The degree to which these will have significance is, at this point in time, a judgment which the core group must make. It is certainly going to be influenced by the nature of the vehicle and the mission. Short duration flights may be the basis for ruling out vibration simulation. Highly maneuverable interceptors with six degrees of freedom may be the basis for including onset G forces and short duration G forces.

Measurement.--The intent is to use the same basic approach as was used in the Dynamic Review. The same Design Scenario is to be used. The measurements include the same devices and techniques. Added to these are the additional capabilities for objective measurements which are now available. They include such measurements as actual and desired values for airspeed, altitude, attitude, navigational position, and power. Other values of interest include stick force and motion, eye point of regard, and precision in setting knobs and inputting through key boards. Physiological measurements can be included such as pupillary response, galvanic skin response, pulse, blood pressure and respiration. As a discussion of methodology, it is appropriate to identify where tests occur and the kinds of test possible. Since the tests selected are a function of the problem, a specific regimen cannot be recommended.

29. Flight Test

Use of the finished design in the vehicle and in the planned circumstances is, of course, the ultimate assurance that the design was good (or not so good). The use of a flight test vehicle prior to approval for production will provide the highest degree of confidence to the decision makers. It involves many people, long term preparation, and extensive support. It is an undertaking of substantial cost and complexity. In a weapon system development program, a flight test is a normal and planned phase. However, it is also common to provide specialized instrumentation and equipment in the cockpit for purposes of the test program. It is highly desirable that the test program also provide for a vehicle test with the proposed crew station configuration. In so far as our methodology is concerned, the test program is essentially a replication of the earlier tests which used mockups and simulation. Flying the Design Scenario in the aircraft provides for the correlation of data with the earlier tests and provides for the correct exercising of the system in the air.

Figure 14. Flight Test

SECTION IV

MANNING, MONEY AND OTHER FACTORS
(lessons Learned)

For questions on the topics of manpower, skills, and time durations, we frequently use the standard reply "It depends."

Where study and refinement are concerned, it is desirable to do enough to assure good solutions. It is not desirable to waste resources beyond that point for little additional gain. How to give specific guidance on that point is a challenge we have not yet resolved. We can only discuss it in indirect terms.

MANNING

A difficulty which we encountered is typical. Our organization was well equipped with instrument and control engineers. As the system problem evolved and our scope expanded it seemed appropriate to do the job with the same approach as we had used for any other job. We assigned it to an engineer. One or another person received extra duties, a job expanded a bit. In other words, we looked to an evolutionary growth and adaptation. Each such project was *frustrating*, the promise of significant improvement was there but the degree of gain realized was disappointing. A more significant commitment was needed in terms of people and support. The commitment was made and resulted in some significant advances in our crew station capability.

The Core Group

A team was assembled as our "Core Group." Resource limits kept it small, which was fortunate. It appears that the smallest group which can provide the knowledge, skill and work is the most efficient and the most effective. Our conclusion was that the core group should have a background which includes human factors, operational employment, engineering, finances, administration, engineering psychology, electronics, computers, and pilotage. All participants should be experienced in R&D. Combinations of skills are found within individuals and, of course, compromise is often necessary. If the group is restricted to a few dedicated assignments it can be augmented for particular issues from time to time. Our core groups were typically comprised of a pilot, experimental psychologist, engineer and a lead person.

At times it seemed that the group was spending more on travel and self education than anything else. This is where management support became decisive in advancing our intent. They provided a continuity of support and confidence which is essential to programs of this magnitude

and type. The results were gratifying. The degree of knowledge and expertise developed by the team greatly enhanced the rapport and communications with the operational crews and in turn the effectiveness of our work.

It quickly became evident that the assignment for the group should not start at Preliminary Design. The team really required the benefit of the problem definition work. Furthermore, the truly significant advances in weapon system capability were dependent upon much more than display design. The systems integration work had shown the very considerable power to be realized by intelligent combinations of existing, but so far, separate, technologies. Preliminary design became the formulation phase for system concepts.

While I have indicated that we typically had four to a core group, the augmentation (part time or short term assignments of additional individuals) effectively raised this to six during the early part of the program (3 to 6 months). Thereafter the supporting teams filled this need.

Our "core group" included, in each program, one and frequently two people with over twenty years experience as pilots including combat experience, instructor duties, handbook writing, R&D flying, and extensive experience at the Instrument Pilot Instructor School (IPIS), Randolph AFB, Texas. Their personal experience augmented by their observations of their many students made them extremely perceptive. They could visualize more of the problems, errors, failures that might affect the situation than we could possibly tabulate. In my opinion, this kind of intuitive ability employed with a representative paper mockup and a design scenario provides a design capability that does not have an equal, or even a minimally acceptable alternative.

This is not advocating the employment of any pilot, but rather ones with rich background experience as those just described. Obviously, these were not hidebound types, their R&D experience at IPIS had prepared them to consider strange alternatives in a reasonably objective way and, in addition, they each had their own quota of creativity.

Skills

In the early days we made much of the idea that the instruments installed in an aircraft reflected, primarily, the requirements of some past vehicle (Ref. 1, p. 3). Today we can temper that view. The engineers and scientists use experience as a stock in trade. When a problem is inadequately defined (and defended/justified), they extrapolate and estimate based upon their experience. They do an excellent job of this too. Unfortunately, in today's environment approximations are not good enough. Warfare systems (and civilian systems) are progressing and expanding too fast, technologically, to allow for the inadequacies of approximations and gut feelings.

There exists some argument for the position of "disciplinarian" with regard to testing and evaluation. Not as a test laboratory would view it. Rather, the concern would be with organization, selection, and batteries of tests designed for system assessment as well as the interpretation of the resulting data. There are not many (if any) rules, as in a discipline, for evaluation of systems where the concern is with the system as a system. Most testing of systems is the compilation of tests upon select components or aspects. There is a need for focus upon the rigor and protocol in the evaluation of complex systems.

Numbers of people are required and many different skills. The work to be performed can be organized into units which are compatible with one another and grouped by skill category.

The work to be performed is responsible for a hierarchical relation of these work groups. The groups must function in some ordered relationship. This relationship includes hierarchical characteristics so as to serve the communication/control/integration needs for development of the system. Thus, the hierarchy is technical.

If you have adequate numbers of people with the right skills and can provide for this technical hierarchy you can proceed.

Administrative or formal organizations might be quite different. It is unlikely that the total activities will be performed by Air Force personnel. In terms of the work to be performed, it is technically dependent upon the skills of the people and independent of the impact of organizational domains (provided they are of good heart).

SCHEDULE

Programs have been conducted in as little as three months and for periods of over three years. That variation in range may raise your eyebrows, but we do think that with proper emphasis even a few months of effort can have a benefit far out of proportion to the small investment made. The first steps to describing the need and understanding the problem can usually be accomplished within three months and is the only significant increase in time over that which is normally expended. The key factor in making it effective is doing it early. If those first steps are started early, then all additional effort can parallel normal time requirements for weapon system programs.

MONEY

In terms of money, the low end of the scale was personnel costs for the three month efforts. The high end of the scale involves the cost of prototype equipment, extensive simulation and flight test.

MANPOWER

Manpower can have the same crazy ranges, from a minimum of 6-8 man months to the very high manning required in complex simulations or flight tests. In our R&D efforts we have had periods where more than 100 individuals were involved.

LESSONS LEARNED

Communication

Communication problems abounded in the day to day activities of getting a simulation that included the vehicle, the flight control, and many of the subsystems. Ground related functions are generally not critical when examining stability and control problems. Computer people, simulator people, pilots, designers, psychologists, etc., each have their own jargon. This jargon includes many assumptions, so taken for granted that they are not only not stated, they are not consciously thought of.

Each person had to be painfully explicit in talking to another - and even then those implicit assumptions could get overlooked. In one instance where the aircraft was to fly a radio beam, the computer person locked the system operation to an algebraically defined line. Said it was the simplest way, "Just common sense" (at least to computer specialists). The experimenter replied that obviously if the crew were flying a radio beam they would not always follow the line "Just common sense" (at least it was to the experimenters). That cost about six weeks of reprogramming. We learned to be explicit, we learned to look at it from the other person's point of view. We learned to check and recheck, to stay constantly in communication. Psychologists learned of the frustrations of a floating ground. Computer people learned about the imponderables in decision making. Pilots learned that work load isn't always work. Our core groups became real cosmopolitans.

Information Management

The formalization of the information gathering is also useful in organizing the data for use in the design process. However, there is always danger in clumping the data according to organizational boundaries and passing it over to design teams. Passing data is not equateable with passing understanding. Expenditures of time and money to provide for the equivalent breadth and level of understanding for every designer (there are thousands) is beyond our reach (even if desired.) Improved structuring of the criteria/needs was the avenue selected along with a series of checks and balances to be employed during the time of development.

It is easy to see that the thousands of details involved in control of a weapon system can lead to a horrendous data management problem. Adequate structuring and formalization are imperative.

Not every person needs every detail but there must always be a way to relate the details, with which a person is involved, back to the real problem and in the proper context.

Re-education

The initial question of why do you want this capability took place a long time ago. Many trials were experienced before we started flying the missions and asking the right questions. One factor which contributed to this was personnel turnover and reorganizations. Each time there was a loss of an experienced person and each time we changed personnel or relaxed our effort, there was an organizational tendency to slip back. Vigilance and a continuing effort at communication are necessary to insure that new personnel are adequately informed/trained.

Organizational

During the course of a program, as we visualized how working relationships should be, it became expedient to simulate some of these. (We could not always go to another organization and demand their involvement experimentally.) For example, systems architecture is the responsibility of a different line organization and we synthesized this function ourselves for purposes of advancing our program. The benefits were many. We gained considerable insight into the interface aspects and improved immeasurably upon our ability to understand and communicate with our associates in the responsible laboratory. Subsequent efforts also had sufficient grounds to effect a productive partnership with specialists in the responsible laboratory.

Control Science

The world of flight control was jolted - it was being faced by a big step in expanded horizons, concerns and responsibilities which heretofore did not receive explicit attention.

It's a shock to be convinced you've been all encompassing and then learn that you've really been addressing 30% of the problem.

The term "Control Science" reflects the recognition and response that has enveloped the organization. It would be unfair (and untrue) to say that this program brought about the recognition and change. That had been growing from the many efforts in the organization. It was simply that the cost and magnitude of the needed simulation effort produced the shock effect in the pragmatic terms of cost, manpower

and time. (Those instrument people who could get by on one man, 6 month and 50-100K for a gadget now are involving/committing 50-100 people, 2-5 years and millions of dollars.)

Cost

That's the bombshell - now to put it in perspective with a weapon system development. All of that equipment is going to be built and installed. The simulator is going to exist and be operated for the weapon system effort. The people to do the design and fabrication are going to be there. What does our methodology do to all of that in terms of manpower and dollars? In the worst case it will not change values appreciably - in better cases it will save dollars, manhours and calendar time.

SUMMARY

It should be recognized that we are talking of a methodology - a way to do the job that is already being done - but to do it more effectively, more efficiently, and with a higher degree of management awareness and control.

With the former procedures it was not only possible but highly probable that some prototype equipment would show up during flight test or Operational Test and Evaluation (OT&E) as unsatisfactory. Redesign, refabrication and retest during (or after) the flight test phase is fantastically expensive. In fact, it is not at all unreasonable for management to accept a compromise in performance because the cost and time alternatives are unacceptable.

Consequently, the really difficult decision is for the R&D organizations. Can they afford the capital investment necessary to address total system considerations? One answer is to couple SPO and Lab resources. Let the SPO get the same result through a Lab contract as they would through industry with the Lab able to retain the capital equipment after the program for use in subsequent efforts.

SECTION V

TEST AND EVALUATION

For decision making purposes on complex systems, the greatest weakness is that a single, direct laboratory test has not yet been devised that takes into account all significant factors and produces an output adequately descriptive of the total performance capability of the system.

Determination of the suitability and acceptability of a specific crew system design cannot be done by some simple, direct measurement. Batteries of tests are used to determine compliance with explicitly stated criteria, standards or specifications. They elicit data about characteristics and performance. Although they may be extensive, comprehensive and expensive, they are not the final word. Decisions must involve human judgment.

There is always a high probability that all significant variables have NOT been identified, characterized and measured.

Final determination of the Yes/No question is, as always, a judgment. It is the role of management to effect the judgment and it is the role of researchers and developers to give credible data and confidence through testing programs and through procedures to augment the incompleteness or inadequacies of testing programs.

Test techniques can run the gamut from paper and pencil tests on a simple component to a full blown flight test program on a complete system. The general approach advocated is one of progressive screening - pursued on two levels. On one level, components and subsystems must be demonstrated to comply with appropriate standards (accuracy, reliability, repeatability, power, RMI, etc.) On the other level the total system must be demonstrated to satisfy the mission needs and the stated criteria of the customer.

The employment of test techniques for the first level (components and subsystem) is well known and understood. It is the second (total system performance) which has not yet achieved an equivalent level of maturation.

The discussion of this chapter is to address second level techniques which can be employed as design aides during system development and the use of first level data in company with the second level techniques for assessment of the system capabilities and potential.

DESIGN SCENARIO

The Design Scenario is a key to the system evaluation technique. It is, in effect, the base line against which all system designs are assessed. It can be employed as a design tool in the development of components and subsystems as well as in a systems effectiveness review.

The Design Scenario is basically a description of the employment of the weapon system in each of the required missions and in the anticipated environment. It provides a time based reference of quantifiable parameters which are relatable to the mission description and of other factors such as crew roles, threat environment, weather and force structure. The documentation takes many forms such as altitude/distance plots, time line description of crew duties, speed/altitude plots and mission profiles.

Development of the Design Scenario is an iterative process with the customer which makes it a particularly valuable device in achieving a mutually complete and detailed understanding of the problem and of the customer's requirements. The development starts with the Statement of Need (SON). It is expanded to describe, as nearly as possible, the designer's understanding of what is wanted, how it is to work and where it will be used. As the design of the system progresses, the scenario can be refined to include the increasing number of details available. Continual coordination and approval by the customer insures that an adequate and mutual understanding exists. It avoids unpleasant surprises to either party when hardware is unveiled.

DYNAMIC REVIEW

A mockup of a proposed design provides the earliest opportunity to review the potential solution in a system context. Gross inadequacies of the placement and relationships are easily discernable. Initial judgment can be made as to the suitability of the design when considered for mission application. It provides an opportunity to screen out gross weakness at a relatively low cost and prior to commitment of expensive fabrication of prototype equipment.

This test develops the time dimension of the mission and examines features of the crew interface within and external to the vehicle. Prime method is through role playing by subject crews and experimenters. Using sorties extracted from the Design Scenario (to produce an Evaluation Scenario), flight crews are to engage in a role playing simulation of the sortie, sequencing through preflight, the sortie flight, post flight debriefing, post flight questionnaires and post flight interviews. The Evaluation Scenario should encompass all challenging flight phases as might be encountered in the intended usage of the vehicle. Additionally, degraded mode conditions should be included in the Evaluation Scenario. Measurement is based primarily upon observation by the experimenters, subject questionnaires and interviews. The crew activities could be

recorded on video tape and all verbal communications tape recorded for subsequent reference or review by the experimenters.

LIGHTING

Lighting requirements have, traditionally, been specified in engineering terms for control of individual components. It, in effect, presumed that if the components were controlled the total result would be acceptable. Experimental work in a T-39 and in the original vertical instrument in the Air Force Advanced Instrument System (Ref. 3) and at a later date in a T-39 aircraft (Ref. 12) gave clear indication of the complexities involving human perception, interactive factors between instruments, various light sources, transparencies, the impact of natural conditions and the mission requirements. Light measuring devices simply do not suffice for an adequate assessment of the vision and lighting of a crew station. A systems assessment technique has been devised for considering the total lighting and vision effects during a mission upon the crew and their performance of the mission. It is a technique similar to the Dynamic Review and relies upon subjective data which is gathered in a systems and mission context. The approach is described in some detail in Appendix E.

EVALUATION

An evaluation of the suitability of the crew system must include consideration of many factors. These include Mission Performance, Degraded Mode Performance, Effectiveness, Training, Efficiency, Survivability, Reliability, Durability, Produceability, Cost Effectiveness, and Maintainability.

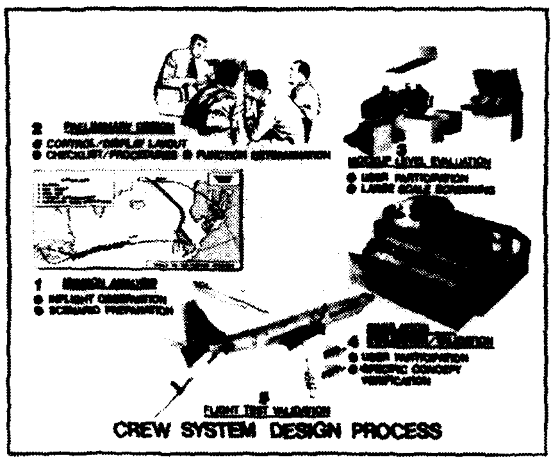
The evaluation process is to acquire data which is relevant to the determination of suitability. Observations about the suitability of the crew system must take into account the reams of measured data and the subjective opinions of the participating crews and experimenters. The process should permit replication and assure credibility.

The factors mentioned above can be grouped into Performance Factors and Physical Factors. In both categories there are measured data and subjective data available. The process should provide a means for merging and assessing the relative merits of these data so as to provide a coherent recommendation to those people responsible for the final decision. We advocate a teaming approach. Experience, appropriate to rendering judgment, is unique for each of the categories.

Performance.--The subject crews and the experimenters have been deeply involved in consideration of the employment of the system in accomplishing the mission. Their varied backgrounds and expertise can greatly enrich the judgmental process. They constitute a team for Performance Assessment. The mechanics for organization and merging of their respective opinions if provided by the use of questionnaires

(APPENDIX D) which provide for a degree of quantification in each of four areas - MISSION EFFECTIVENESS, WORKLOAD, EMERGENCY and CREW ACCOMMODATION. The mission effectiveness area is further divided into five specific portions - TAKEOFF, ENROUTE, REFUELING, CARGO DELIVERY, and LANDING. (Refueling and cargo delivery are mission dependent words which would be replaced with appropriate labels.) Each crew member and each participating experimenter should have the opportunity to digest the experience, participate in post experiment debriefings, interviews and discussions as an aide to crystallizing individual reactions. The experimenters' forms should consider the cumulative effect of all subjects. Standard statistical treatment can then be applied.

Physical.--The physical area of concern is generally characterized by the ability to obtain objective measurements. However, even in this area there is need for subjective observations. Consideration of logistics, computer architecture, flight control, etc., require vastly different areas of expertise. Consequently, the team must be carefully selected. It should include representatives from areas such as: Logistics, Maintenance, Avionics, Training, Flight Control, Behavioral Science, Life Support, Lighting, Electronic Warefare, Computer Science, Control/Display, Manufacturing, and Aeronautics. This team will require a credible judgment. They must be briefed on the equipment design and the rationale for the design; provided data on test performed; and provided the opportunity to examine the equipment. Their judgments are collected by means of questionnaires (APPENDIX C) which can be statistically treated as in the case of the performance assessment.



CREW SYSTEM DESIGN PROCESS

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The listing presented here is a sampling of the past 25 or so, years. From it you may make observations on the scope, magnitude and duration of efforts in reaching our present state of awareness and capability. Also observable are changes in emphasis through the time period and variations in the number of efforts reported for various time periods. For the very early years there is an abundance of reports on activities for individual displays. With the passage of time there were lesser numbers of reports but those reported are on larger concerns.

An interesting observation is that those reports which provide the basis and threads of development for the system philosophy, espoused in this report, are more often from areas of man-machine and human factors activity. I would hazard the opinion that engineers in system development were really restricting the scope of their concerns to hardware whereas when the human element was introduced, the systems connotation necessarily included not only behavior but motivation - leading naturally to questions of requirements.

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APPENDIX A

MOCKUP CATEGORIES

A full scale mockup of the crew areas is a prime requirement for early viewing of interactive factors of the design concept. As the design progresses, more detailed examinations can be effected but the demands upon the accuracy, fidelity and completeness of the mockup change. Consequently, three categories of mockups have been defined to provide for these differing requirements. These are defined as follows:

Class A. The highest degree of accuracy and fidelity is required for this category. All dimensions are to be accurate within +/- 0.1 inches. All geometry, affecting the crew, is to be present (wall, surfaces, windows, doors, seats, etc.) The windscreens, windows, canopies or other transparencies are to be either the actual production line versions or are to be fabricated of the planned material to the exact dimensions and with the same reflective and transmissive characteristics. All control or input devices are to be included or simulated with correct motion, breakout forces, friction, resistance and feel. Surface texture, reflectance and color must accurately reflect the intended production characteristics. The total lighting system must be included to permit the full spectrum of capabilities to be demonstrated. The communication system should be the planned system or have identical audio characteristics. Provision should be made to isolate extraneous sounds and to introduce representative sounds. All instruments, lights, annunciators, switches, controls, pedals, adjustments, and visual or audio effects must be faithfully represented as their intended functioning. In so far as practical, the actual hardware should be used. In essence, its appearance to the crews should be such that they could not distinguish it from the production version. Note that behind the scenes equipment for signals and drive of the cockpit equipment could be pure simulation techniques.

Class B. A medium degree of fidelity is considered appropriate. Structural dimensions should be accurate to +/- 0.75 inches where they affect crew placement, movement or performance. Windows, canopy and other openings should be represented but substitute materials may be used. The three dimensional aspects of control and display devices should be represented by any suitable medium, they do not have to function. Instrument faces and placards may be drawings or pictures. The communication system, however, must simulate correctly the operational concept.

Class C. This, the simplest mockup with a minimum degree of completeness, provides approximations of shape, size and position of control/display surfaces and structure. The mockup may be built of inexpensive material (e.g., cardboard, foam core, plywood). Pictorial means (e.g., line drawing, photostat, picture) will suffice to represent instruments, placards, knobs, switches, controls and other devices to be used by the crew. The communication system, as in the others, should be functional and interconnected with external stations to provide for role playing interchange with towers and other stations.

APPENDIX B

EXPERIMENTER'S OBSERVATION

This form is designed for use in the instance of a crew complement of three. Based upon prior experience, the experimental team identifies points in each sortie where they are likely to be workload related problems. These are identified in series (as 1, 2, 3, etc.) When the mock flight passes that point in the scenario, the experimenter records his assessment of the observed workload for each crew member.

EXPERIMENTER'S OBSERVATION

WORKLOAD

SORTIE: ____________________

	______ crew position	______ crew position	______ crew position
1.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
2.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
3.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
4.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
5.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
6.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
7.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
8.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
9.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10
10.	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10	! .... ! .... ! 0 5 10

APPENDIX C

PHYSICAL ASSESSMENT FORM

AREA BEING ASSESSED: (check one area only, use separate sheet for additional areas being assessed.)

LOGISTICS	TRAINING	FLIGHT CONTROL
MAINTENANCE	LIFE SUPPORT	POWER PLANT
RELIABILITY	LIGHTING	COCKPIT GEOMETRY
SURVIVABILITY	HUMAN FACTORS	ENTRY/EXIT, ESCAPE
	AVIONICS	INSTRUMENTS/CONTROLS

Check the number which best reflects your opinion.

1. Not acceptable: Unsafe, impractical, failure prone, enormously expensive.

2. Not acceptable: Potentially correctable with major redesign.

3. Marginal: Discrepancies which can seriously lower the probability of mission success or survival.

4. Marginal: Discrepancies which are serious and can lower the probability of mission success or survival.

5. Marginal: Discrepancies which have significant impact and which reduce the probability of mission success.

6. Conditionally Acceptable: Discrepancies which have a significant impact and which must be corrected. Not cost effective.

7. Conditionally Acceptable: Discrepancies which have a small but significant impact and which should be corrected.

8. Acceptable: Minor discrepancies which should be adjusted.

9. Acceptable: Very minor discrepancies which do not have significant impact.

10. ACCEPTABLE: Completely acceptable.

____
(name)

COMMENTS: (Please expand upon your reasons for the rating you selected.)

APPENDIX D

PERFORMANCE ASSESSMENT FORM

____

Crew Position

AREA BEING ASSESSED: (check one area only, use separate sheet for additional areas assessed)

Mission Effectiveness	Other Areas
TAKEOFF	WORKLOAD
ENROUTE	EMERGENCY (Degraded mode)
REFUELING	CREW ACCOMMODATIONS
CARGO DELIVERY	
LANDING	

Check the number which best reflects your opinion.

1. Not acceptable: Unsafe. I won't fly this cockpit.

2. Not acceptable: Cannot perform the mission. I won't fly this cockpit.

3. Marginal: Performance entails great difficulty/risk. Probability of a successful mission is under 10%. I don't want to fly this cockpit.

4. Marginal: Performance is very demanding. Probability of a successful mission is under 50%. I don't like flying this cockpit.

5. Marginal: Performance is demanding. Probability of a successful mission is under 70%. I don't like flying this cockpit.

6. Conditionally Acceptable: Requires modification. I can fly this cockpit.

7. Conditionally Acceptable: Requires changes or adjustments. I don't mind flying this cockpit.

8.	Acceptable:	Requires minor changes. I like flying this cockpit.
9.	Acceptable:	Requires minor adjustments. I want to fly this cockpit.
10.	ACCEPTABLE:	Completely OK! I would like an assignment to fly this cockpit.

____

(name)

COMMENTS: (Please expand upon your reasons for the rating which you gave.)

APPENDIX E

LIGHTING EVALUATION

The lighting tests are intended to cause a more critical evaluation of crew station lighting during the mockup and simulation phase of the development. This is done by focusing the subject's (crew) attention on the question of adequate lighting, by causing them to use the lighting. The use of a model aircraft with scaled external cell formation lights is proposed to permit a meaningful evaluation of daylight cockpit information legibility.

For the lighting evaluation it is essential that a Class A mockup (Appendix A) be used. All light sources, including displays, must be presented in a faithful representation of the production design. The mockup is to be used in a room where all external light sources can be controlled from total darkness up to a level representative of high ambient sunlight.

NIGHT TESTS

With the ambient set for total darkness and experimenters in the crew seats, the lighting controls are to be cycled throughout the ranges and combinations available. The experimenters are to scan for reflections in the windows and windscreen which could be misinterpreted as stars, ground lights or other airborne vehicles. All such reflections are to be identified and graphed for comparison with the stated criteria.

> When evaluating the effect of reflections from the windscreen, windows, etc., small lighted real-world visual scenes could be used external to the cockpit to act as a backdrop for evaluating the seriousness of reflections. Such scenes would have to be moved to locations behind reflections a crew member considers objectionable. By varying the luminance levels in the scene, be it ground terrain, cities, airports or star fields, and noting when a crew member considers the reflection objectionable, a relationship between real-world observation requirements and the lighting mockup conditions could be established.

With the ambient totally dark, the experimenters are to adjust comfortable levels for the prime flight instruments and for each of the additional controlled groups of lights. The experimenters will scan for too bright or too dim indications.

As a means of giving the experimenters a valid reference for establishing dark adapted cockpit lighting control levels, a scaled externally lighted model of an aircraft will be used to simulate a night cell formation flying task. A KC-135 is to serve as the model. Figures 15a and 15b give the approximate locations of navigation and beacon lights on the reference KC-135 aircraft with its external lighting configured for cell formation flying. Table 1 gives the lighting conventions for the lead and up to four trailing KC-135's, both in the cell formation and when the respective receiver aircraft approach to within one half mile of the tanker they are to dock with. Figure 15c shows the cell formation distance, altitude and sighting angle relationships between adjacent aircraft flying the cell formation. Table 2 gives the approximate dimensions that a KC-135 model should have if placed at a viewing distance of 20 feet from the pilot/copilot eye point of regard in the mockup in order to correctly simulate an actual lead KC-135 one nautical mile ahead. The model must also be equipped with lamps having the scaled luminous intensities and colors indicated in Table 3. All lamps must subtend an angle of less than one arc minute (0.291 milliradians) at the experimenter's eye or 0.07 inches in cross sectional dimension on the 20 foot viewing distance KC-135 model in order for the luminous intensities of Table 3 to accurately represent the actual brightness of the lead aircraft external lighting. The model lights should be capable of being dimmed to simulate reduced visibility flight conditions.

With the lighted KC-135 model positioned at about a 5 degree down pitch from the experimenter's eyes and 20 feet distant the model external lighting will be turned on. The experimenters will assess the cockpit lighting levels set previously and, if necessary, adjust the crew station lighting controls to achieve and maintain safe visual contact with the simulated lead cell formation aircraft. With the lighting controls set in this manner the following controls should, as a minimum, be located and operated: interphone control panel, liaison radio frequency selection, anti-icing controls, warning light bright-dim switch, cabin pressure controls, fuel tank controls, oxygen regulator control, J-4 compass, UHF command radio frequency selection. The experimenters should note any controls found to be difficult either to find or to set properly following location.

Auxiliary interior lighting may, at times, be employed during flight phases requiring cell formation flying or rendezvous with other aircraft. It should be evaluated by the experimenters. Lights that should be considered for this test (subject to the experimenters' experienced need for such lights in actual missions) include: spot and map reading lights, forward or side panel flood lights, and the control stand flood light. The auxiliary lights should actually be employed by the experimenters for typical tasks that can occur during cell formation flying, possibly including: reference to navigation maps, reading navigation waypoints, reading flight plans, reading and then setting secure communications frequencies, reading receiver aircraft

fuel allocations, and so forth. The experimenter's ability to maintain visual contact with other cell formation aircraft while performing normal flight control functions should be assessed during the conduct of these reading/control tasks, as should the adequacy of the auxiliary lighting.

Electronic displays should be turned on and the adequacy of their dimming control to produce satisfactory brightness settings should be assessed. The quantity of information depicted on the displays during this test should be typical to high. The brightness uniformity of display information should be evaluated and reading difficulties noted. The lights representing the lead cell formation aircraft should again be observed and any changes in their perceived visibility noted. Under these conditions, functions requiring pilot inputs or interactions such as entering communications frequencies or navigation data should be exercised to evaluate the adequacy of their illumination. Difficulties in locating controls or in achieving correct entries should also be noted.

Selected warning, caution and advisory signal lamps should be activated. The experimenters will assess the adequacy of the brightness of the master warning and caution lamps with respect to their "attention getting" capability. They will also assess the associated annunciator panel indications for excessive/inadequate brightness and for the legibility of the legends portrayed on them. Several annunciations of each color used should be activated to permit evaluating the adequacy of the brightness and color uniformities present between annunciators, and to evaluate whether warning, caution and advisory colors are readily distinguishable from one another.

Based on the warning, caution and advisory signal annunciated the experimenters should follow standard system checkout procedures. The signal annunciations selected for activation should be chosen to cause the experimenters to have to locate, read and take normal precautionary control or fault verification measures. The experimenters will evaluate the legibility of the night lighted controls, panels and displays encountered while carrying out these procedures. As a minimum, at least one of each type of flight safety or mission critical function category (i.e., engine parameters, electrical, nevigation system, fuel system, etc.) should be evaluated.

DAY TESTS

Daylight testing is primarily concerned with assessing the effectiveness of switches, displays, annunciator lights and their respective lighting controls. The experimenters' task is to assess the crew's ability to perceive the on/off state of indicator lights or, alternatively, the ease of reading information portrayed on light emitting displays, readouts or switches. The experimenters operating in a role playing mode should read navigation, communications, fuel information and operate the associated controls. It is, therefore, necessary that any CRT or alpha-numeric readout displays used in the aircraft be operative.

Typical control actions including data entry, mode changes and switch setting/activations associated with performing a particular task should be carried out. The ease of locating and reading or determining the status of control and display functions should be assessed regarding their color, brightness, size and color and brightness uniformities. Problems encountered in control of legibility should also be assessed.

There are three atmospheric illumination conditions that should be evaluated. In each the impact of shadows on control-display legibility and the ability to adjust available lighting controls to compensate for the effects should be assessed. The three atmospheric illumination conditions may be summarized as follows:

1. Sky at 2,000 foot Lamberts (fL) luminance with a mobile collimated 10,000 foot-candle (fc) illuminance source capable of being directed through the mockup side windows onto the instrument panels.

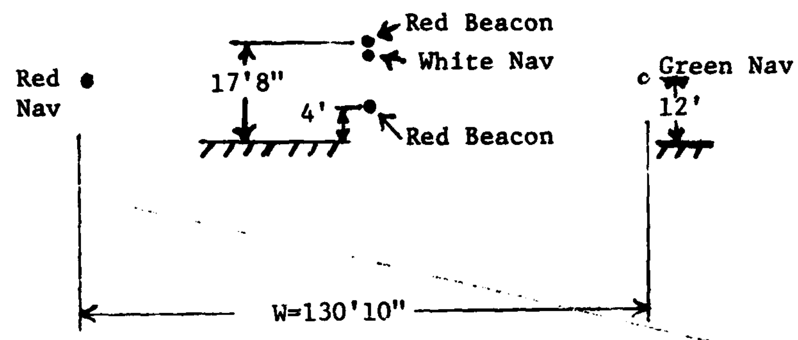
2. Diffuse surround sky illumination of luminance 10,000 fL located just outside the lighting mockup's windows.

3. Sky at 2,000 fL luminance with a mobile collimated 10,000 fc illuminance source of no greater than 5 degree angle subtended at the pilot's eyes (sun actually subtends 0.5 degrees) and directed through the windscreen to act as a glare source.

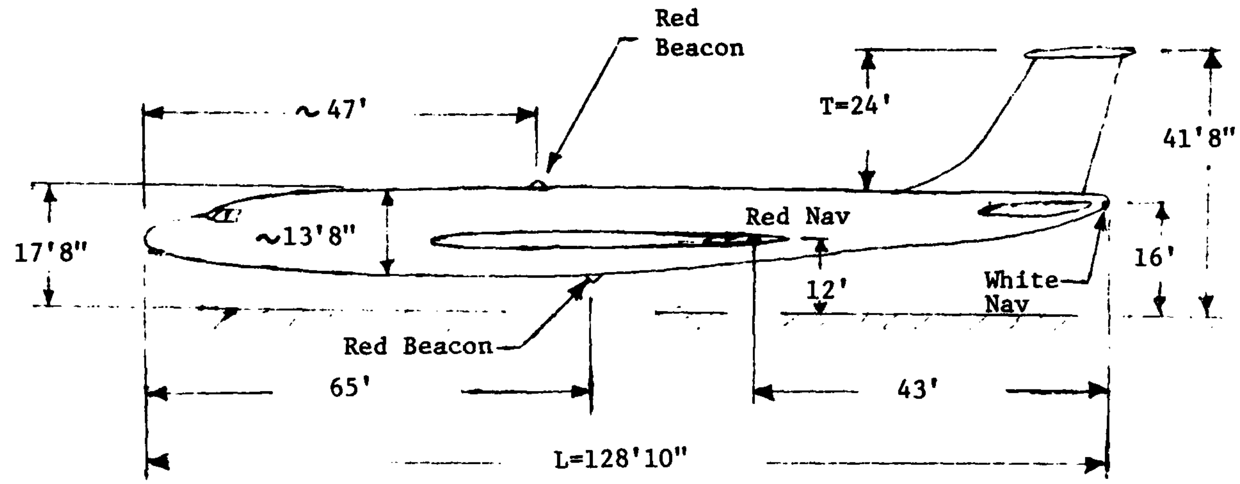
The first illumination condition corresponds to flying on a clear day with the sun directly incident on parts of the panels and casting shadows elsewhere. General illumination by the sky also produces shadows, the difference being that the sky induced shadows do not change materially as the aircraft is maneuvered, whereas the sun induced shadows can change as a function of time. The experimenters should, therefore, attempt to identify information that is deficient in legibility both while the solar source is fixed and while it is being moved to new locations. The diffuse illumination condition corresponds to flying in a light haze, mist, and near or in clouds and results in a high general illumination level in the cockpit which severely affects the legibility of some types of displays. The diffuse surround illumination condition produces light scatter in the pilot's eyes that is perceived as looking through a veil of luminance. This can be the most severe of the three conditions since it degrades the legibility of reflective electromechanical instrument displays and panels. The visual perception of veiling luminance is dependent primarily on the visual angle between the sun and the location of the cockpit information being read, with reductions of the angle increasing the perceived veiling luminance level. Thus, even with the sun's location fixed with respect to the mockup, normal scanning of cockpit information will introduce dynamic adaptation as a secondary evaluation factor. Introducing the KC-135 model used for night test would provide additional test realism in that it would require accommodation to an external target. Temporary exposure to small target-sun angular

separations would also permit a more realistic evaluation of crew station information in the presence of dynamic adaptation conditions.

Experimenter assessment of the following cockpit design factors should be made: (1) the effectiveness of window shades, glare shields, sun visors, or any other light blocking devices present in the cockpit; (2) the effect on cockpit information legibility of shadows cast by the cockpit structure and its contents; and (3) glare resulting from either direct or indirect reflections of the sun from cockpit surfaces, including those of the windows and windscreen. To conduct a meaningful test of these factors, the relative size of the sun need not be accurately simulated, but the light it produces would have to be collimated to accurately simulate a distant light source. Collimation of the solar source is also necessary to adequately simulate the degradation produced by veiling luminance on the legibility of cockpit information when the sun is present within the instantaneous field of view of a crew member's eyes.

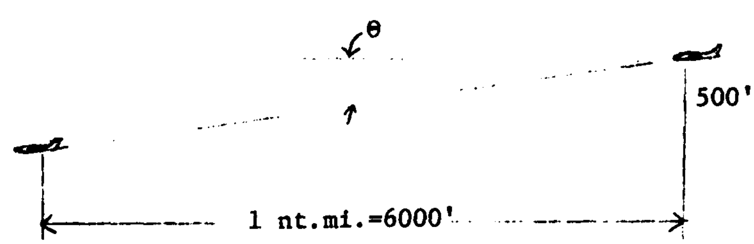


a. Rear View of KC-135 Cell Formation Lighting



b. Side View of KC-135 Cell Formation Lighting

$\theta = 4.76° = 83.1mr$



c. Aircraft Relationships in the Cell Formation

Figure 15. Cell Formation Lighting

TABLE 1

EXTERNAL LIGHTING CONVENTION FOR
CELL FORMATION ON KC-135 AIRCRAFT

	Navigation Lights+	Upper Rotating Beacon	Lower Rotating Beacon	Formation
Lead	Steady/Bright	Red	Red	Cell
	Steady/Bright	Red	Off	Receiver 1/2 Mile*
#2	Steady/Bright	Wht	Wht	Cell
	Steady/Bright	Wht	Off	Receiver 1/2 Mile*
#3	Steady/Bright	Red/Wht	Red/Wht	Cell
	Steady/Bright	Red/Wht	Red/Wht	Receiver 1/2 Mile*
#4	Steady/Bright	Wht	Red	Cell
	Steady/Bright	Wht	Off	Receiver 1/2 Mile*

Left - Red
Right - Green
Tail - White

* Receiver Pilot Director Lights turned on.

\+ Upper and lower navigation fuselage lights are off when beacons are on.

TABLE 2

KC-135 MODEL SCALED FOR VIEWING AT 20 FEET

	KC-135 Dimensions in Feet	Model* Dimensions in Feet	Model* Dimensions in Feet
Fuselage Length	129	.43	5.16
Wing Span	131	.437	5.24
Fuselage Height	14	.047	.56
Fuselage Width	12	.04	.48
Tail Height above Fuselage	24	.08	.96
Altitude Difference	500'	1.67	20

* Model Dimensional Scaling Factor, K, for viewing at a 20 foot distance.

K = 20' x 6000' = .003333 ft/ft

K = (20 x 12") / 6000' = .0400 in/ft

TABLE 3
KC-135 Cell Formation Exterior Light Intensities/Flash Rates

Type	Color	Actual Luminous Intensity[2] I_a	Perceived+ Luminance L_p	Model* Luminous Intensity I_m
Navigation Light	1. Left Wing Tip Filtered Aviation Red	40cd	52fL	440ucd
	2. Right Wing Tip Filtered Aviation Green	40cd	52fL	440ucd
	3. Tail - White	20cd	26fL	220ucd
Rotating Beacon (Anti-Collision Lights)	Upper & Lower Fuselage Aviation Red	Effective Values[3]		
		100cd	131fL	1100ucd
		Approximate Peak Instantaneous[4]		
		330cd	432fL	3630ucd

* Scaling Equation for Model lamp luminous intensities

$$I_m(cd) = \left(\frac{r_m}{r_a}\right)^2 I_a(cd) = \left(\frac{20'}{6000'}\right)^2 I_a(cd) = 1.1\text{x}10^{-5} I_a(cd)$$

$$I_m(ucd) = 11\ I_a(cd)$$

+ Perceived Luminance of Point Source of Light[5]

$$L_a(fL) = L_m(fL) = \pi\ \frac{I_a(cd)}{A_a(ft^2)} = 4\ \frac{I_a(cd)}{d_a(ft)^2} = 1.31 I_a(cd)$$

$d_a(ft)$ - perceived point-source diameter = (.000291 rad)(6000') = 1.75ft

1. Values in direction for cell formation viewing in candela(cd).
2. Minimum required by Mil-L-6503.
3. Effective Intensity as defined by Mil-L-6503.
4. Maximum Instantaneous Intensity of flash.
5. Human averages light over 0.29 milliradian visual angle.

TABLE 3 (cont'd)
Anti-Collision Light Flash Rate Requirements

Taken from
MIL-L-6503G(USAF)

*3.3.1.3 Flashing characteristics. The arrangement of the system, i.e., number of light sources, beam width, speed of rotation, et cetera, shall be such as to give an optimum effective flash frequency of 90 cycles per minute. The effective flash frequency shall be not less than 40 nor more than 100 cycles per minute except when the system includes overlaps created by more than one light source. In overlaps, effective flash frequencies shall not exceed 180 cycles per minute. The effective flash frequency is established as that frequency at which the aircraft's complete anticollision light system is observed from a reasonable distance.

3.3.1.4 Color. The color of all light emitted shall be aviation red.

3.3.1.5 Light intensity. The minimum light intensity for each light in all vertical planes measured with the red color filter in place and expressed in terms of effective candlepower as determined by the formula below shall equal or exceed the values specified in column 3 (entitled "Required") of table IV:

$$I_E = \frac{\int_{t_1}^{t_2} I(t)\,dt}{0.2 + (t_2 - t_1)}$$

Where I_E = Effective candlepower

$I(t)$ = Instantaneous candlepower as a function of time

$t_2 - t_1$ = Flash time interval in seconds

Note: Normally the maximum value of effective candlepower is obtained when t_2 and t_1 are so chosen that the effective candlepower is equal to the instantaneous candlepower at t_2 and t_1.

*3.3.1.6 Flash frequency vs effective intensity. The rise and decay characteristics of high-current lamps flashed by electrical means are such that the intensity may not decay during the "off" period to an acceptable level of less than 0.30 times the peak intensity. In such cases the flash frequency may be reduced to obtain an adequate decay provided that the effective light intensity (see table IV) is increased by twice the percentage of flash frequency reduction below 90 cycles per minute. As an example, if the flash frequency is 45 cycles per minute (a decrease from 90 cycles per minute of 50 percent), the effective intensity requirements of table IV shall be increased by 100 percent.